# SCHOOL OF CIVIL ENGINEERING

# INDIANA DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

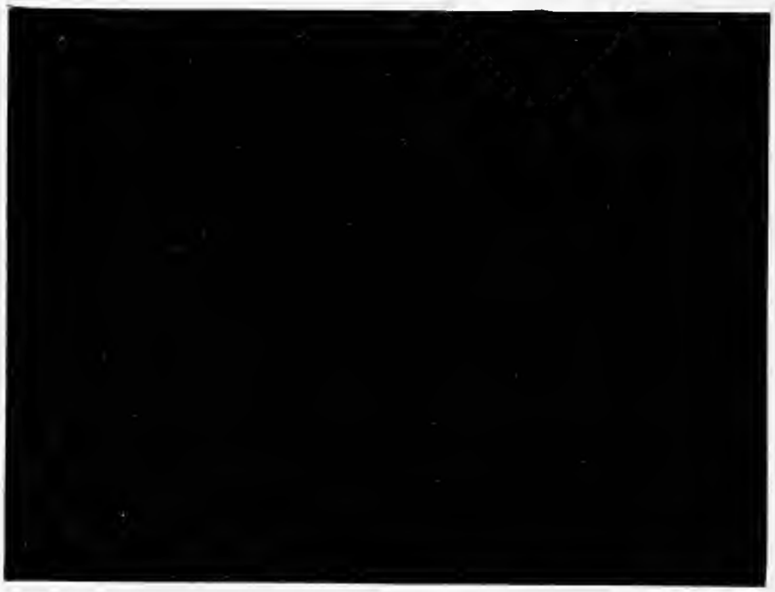
Final Report

FHWA/IN/JHRP-87/11 -1

## MATERIAL CHARACTERIZATION OF HOT-MIX RECYCLED BITUMINOUS PAVEMENTS

L.E. Wood
A.S. Noureldin

PURDUE UNIVERSITY



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Material Characterization of Hot-Mix
Recycled Bituminous Pavements

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|---|---|---|
| TO: | Harold L. Michael<br>Joint Highway Research Project | December 1, 1987<br>May 4, 1988 Revised<br><br>Project: C-36-21G |
| FROM: | L. E. Wood<br>Research Engineer | File: 2-8-7 |

Please find attached the draft Final Report entitled "Material Characterization of Hot-Mix Recycled Bituminous Pavements". It was prepared by L. E. Wood and A. S. Noureldin, and represents the work of A. S. Noureldin of our staff

This report contains 9 chapters. Chapter 2 describes the materials and equipment used. Chapters 3 and 4 present the research work conducted to evaluate and characterize the recycled binder. Chapter 5 gives the experimental design and the testing program together with some theoretical background for the study of the major mechanical properties. Evaluation and characterization of recycled compacted mixtures is included in chapter 6. Long term performance of hot recycled mixtures was investigated in chapter 7.

This report is presented for review and approval as evidence of fulfillment of the objectives of this project.

Respectfully,

Lenard E Wood

L. E. Wood
Research Engineer

cc: A. G. Altschaeffl
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TECHNICAL REPORT STANDARD TITLE PAGE

| | | |
|---|---|---|
| 1. Report No. FHWA/IN/JHRP-87/11 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle Material Characterization of Hot-Mix Recycled Bituminous Pavements | | 5. Report Date December 1, 1987; May 4, 1988 Revised |
| | | 6. Performing Organization Code |
| 7. Author(s) L. E. Wood and A. S. Noureldin | | 8. Performing Organization Report No. JHRP-87/11 |
| 9. Performing Organization Name and Address Joint Highway Research Project, Civil Engineering Building, Purdue University, West Lafayette IN 47907 | | 10. Work Unit No. |
| | | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address Indiana Department of Highways, State Office Building, 100 N. Senate Avenue, Indianapolis IN 46204 | | 13. Type of Report and Period Covered Final Report |
| | | 14. Sponsoring Agency Code |

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Study title is "Material Characterization of Hot-Mix Recycled Bituminous Pavements.

16. Abstract

A detailed laboratory investigation was performed to characterize the performance of the hot mix recycled asphalt pavement in comparison with a virgin mix. A virgin mixture and three recycled mixtures were evaluated. Marshall size specimens were fabricated and evaluated using the pulse velocity, resilient modulus, indirect tensile strength, Hveem stability and Marshall stability tests. In addition the recycled binder itself was evaluated using a stage extraction technique and the thin film oven test results. Long term aging of recycled mixtures was also studied. Subjective conclusions were established for the performance of recycled mixtures under various conditions.

Virgin mixture stiffness and strength parameters were higher than those of recycled mixtures. However, long term aging properties of two of the recycled mixtures were better than the virgin mix, especially when regarding the failure tensile strain. The thin film oven test and the indirect tensile test were identified as additional criteria for the choice of type and amount of recycling agent to be used. The results of this study will provide the highway engineer with a better understanding of the effect of different factors on the tensile and resilient characteristics of hot recycled bituminous paving mixtures

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|---|---|
| 17. Key Words Hot-Mix Recycling, Rejuvenator Resilient Modulus, Indirect Tensile Strength, Pulse Velocity, Long Term Performance, Aging | 18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield VA 22161 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 143 | |

Form DOT F 1700.7 (8-69)

FINAL REPORT

# Material Characterization of Hot-Mix Recycled Bituminous Pavements

by

L. E. Wood

and

A. S. Noureldin

Joint Highway Research Project
Project No.: C-36-21G
File No.: 2-8-7

Prepared for an Investigation
Conducted by the
Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the
Indiana Department of Highways
and the
U.S. Department of Transportation
Federal Highway Administration



Purdue University
West Lafayette, Indiana

December 1, 1987
May 4, 1988 Revised

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# CHAPTER 1

# INTRODUCTION

## 1.1. Background

Most of the highway network in the United States has been constructed and provided many years of service. Thus, the present day major concern for most of the highway and transportation agencies is not one of designing and building new pavements, but is to obtain the most effective service with the minimum cost from the existing pavement systems. In most cases this means the extension of the pavement life beyond its design life through rehabilitation and/or overlays. Most rehabilitation and maintenance alternatives are costly, geometrically restricted, energy consuming and material intensive.

Pavement recycling is simply a technique in which hardened deteriorated old pavement can be processed and reused. The fundamental concept lies in softening the old binder fraction by the addition of softening agents so that the original properties of the old binder are restored. In some cases the addition of new asphalt is required.

Pavement recycling technology has become an increasingly attractive rehabilitation alternative as it offers several advantages over the use of conventional materials. The quantity of materials salvaged by recycling increases every year and is expected to continue as highway agencies become more involved in resurfacing, restoration, rehabilitation and reconstruction programs. The unstable cost of asphalt cement, decreasing supply of locally available quality aggregates, geometric difficulties of adding overlay thickness and the growing concern over waste disposal have made recycling an environmentally and economically attractive alternative.

Recycling operations have already experienced a rapid growth in recent years. This growth has resulted from increased awareness of the potential for cost savings and material conservation. More importantly, the effort put forth by the equipment manufacturers has also increased. The recent years have seen rapid advances in pulverizers, millers, and hot mix plants that facilitate recycling operations. Millions of tons of hot mix recycled pavements have been used in the present highway system. Recycled mixture design has been developed using the test methods and criteria that have been historically utilized for conventional asphalt concrete pavement. Initial results indicate that these methods and criteria are generally acceptable.

## 1.2. Problem Statement

The increase in recycling operations has resulted in an increased awareness that the recycled materials must be properly characterized in order to ensure a quality pavement. The cost and energy savings obtained during construction may be lost through excessive maintenance if the recycled pavements undergo severe deterioration. Initial indications are that a quality pavement is being constructed using conventional design methods. However, these pavements have not been in service long enough to permit a definite judgment of their proper long term performance.

An investigation of all possible bituminous pavement recycling techniques would necessarily entail a research effort that is widespread and time consuming. Therefore, it is the intention of this study to investigate the material, mixture and mechanical properties of hot-mixed recycled bituminous pavement.

There are several unanswered questions in the area of hot-mix recycling; distribution of the recycling agent, homogeneity, compatibility and rate of hardening of recycled mixes when compared with a conventional mix. There is also still a need for assurance that effect of weathering, long term aging and its effect on physical properties of recycled

bitumen and the effect of repeated loads on the mixture after it has been recycled and compacted in the roadway are not problems.

## 1.3. Objectives

The objectives of this study are not to prove the feasibility of recycling. Recycling is a proven fact and many successful processes exist. Material characterization is an important step in all recycling methodologies that are used to identify the properties and the amount of rejuvenation and virgin material required to achieve a mixture that will have the properties and performance equivalent to a new pavement structure built with virgin material.

The research objectives of this study are:

1. Establishment of the effectiveness of mixing on the dispersion and distribution of the recycling agent to produce a homogeneous mixture.

2. Determination of the effect of weathering by means of artificial laboratory aging on the rejuvenated asphalt materials.

3. Evaluation of the effect of time on mechanical properties of the recycled mixes by means of pulse velocity, resilient modulus and indirect tensile strength tests. Hveem and Marshall stability tests are also to be included as a part of this evaluation.

# CHAPTER 2

# MATERIALS AND EQUIPMENT

## 2.1. Materials

### 2.1.1. Recycled Asphalt Pavement (RAP)

A stockpile of representative salvaged asphalt pavement was obtained for laboratory evaluation. The material used was milled from US 52 (south of Indianapolis, Indiana) and randomly selected under the supervision of Indiana Department of Highways personnel for the purpose of this study. Sampling of the laboratory created stockpile was also randomly selected to obtain statistically representative asphalt materials for the study.

Samples of the RAP were randomly chosen and reduced in size and characterized. Asphalt extraction and recovery was conducted using ASTM D 2172 method "A" and Abson Method ASTM D 1856 respectively. The salvaged binder was characterized by means of penetration, softening point and viscosity tests. Amount of asphalt present was determined and the salvaged aggregate obtained from extraction was characterized by sieve analysis.

Tables 2.1 and 2.2 give the characteristics of the extracted hard asphalt and the gradation of salvaged aggregate respectively. The values obtained were an average of 10

Table 2.1: Characteristics of Extracted Hard Asphalt

| Test | Value |
| --- | --- |
| Penetration, 77$^{\circ}$F, 100 gm, 5 sec. | 28 |
| Viscosity, 140$^{\circ}$F, Poises | 20,888 |
| Kinematic visc., 275$^{\circ}$F, c. st. | 726 |
| Softening Point, $^{\circ}$F | 137 |
| Asphalt Content (Total wt.) | 6% |

Table 2.2: Gradation of Salvaged Aggregate

| Sieve size | 3/8 | #4 | #8 | #16 | #30 | #50 | #100 | #200 |
|---|---|---|---|---|---|---|---|---|
| % Passing | 98 | 74 | 62 | 44 | 28 | 15 | 7.5 | 5 |
| IND. spec. for #12 surface | 96-100 | 70-80 | 36-66 | 19-50 | 10-38 | 5-26 | 2-17 | 0-8 |

samples. The Indiana State Highway standard specifications (69) for #12 surface were also included in Table 2.2 for comparison purposes and for future determination of the feasibility of the salvaged aggregate for use as a high quality hot surface mix. The recovered aggregate consisted mainly of crushed limestone as coarse aggregate (material retained on #4 sieve) and natural sand as fine aggregate (material passing #4 sieve). The sieve analysis of the salvaged aggregate indicated a gradation which is within the specification for #12 surface.

### 2.1.2. Recycling Agents (Rejuvenators)

It is imperative to indicate that the terms recycling agents, rejuvenating agents, rejuvenators and softening agents used throughout this thesis are all equivalent and represent any material used to soften the hardened asphalt binder present in the RAP.

Three types of recycling agents were selected for use in combination with the age-hardened salvaged asphalt binder. The selections were based on their previous usage in other recycling techniques, the wide variation between their nature and the knowledge of their physical and chemical properties. The following recycling agents were used:

1. AC-2.5, ASTM designation, produced by Amoco Oil Company.

2. AE-150, Indiana designated high float medium setting type asphalt emulsion, supplied by McConnaughy, Inc.

3. Mobilsol-30, ASTM designated type 101 oil, produced by McConnaughy, Inc.

Tables 2.3 to 2.5 give the characteristics of AC-2.5, AE-150 and Mobilsol-30 respectively.

### 2.1.3. Virgin AC-20

The three recycling agents were to be used to restore the old binder present in the RAP to the AC-20, ASTM designation, classification range. A virgin AC-20 was obtained from Amoco Oil Company for comparison purposes between virgin binder and recycled binder and between virgin hot mixes and recycled hot mixes as well. Virgin AC-20 was not used in any combination with recycled mixtures. Table 2.6 gives the characteristics of AC-20. It would be imperative to indicate that the choice of AC-20 was based on its usage in the state of Indiana to produce hot mix asphalt pavements.

### 2.1.4. Virgin Aggregate

Crushed limestone and local sand were selected to represent the coarse and fine aggregate material for the virgin aggregate (the same as recovered salvaged aggregate). The aggregate has been stored in the Purdue University

Table 2.3: Characteristics of AC-2.5

| Test | Value |
|---|---|
| Penetration, 100 gm, 77°F, 5 sec., 0.1 mm. | 200 |
| Absolute viscosity, 140°F, Poise | 292 |
| Specific Gravity, 77°F | 1.024 |
| Ductility, 77°F, 5 cm/min., cm. | 150 + |

Table 2.4: Characteristics of AE-150

| Test | Value |
|---|---|
| Residue by Distillation | 68% |
| Penetration of Residue | |
| 100 gm, 5 sec, 77°F, 0.1 mm | 200 |
| Specific Gravity of Residue, 77°F | 1.01 |
| Float, 140°F, sec. | 1200+ |
| Absolute Viscosity of Residue, | |
| 140°F, Poise | 270 |

Table 2.5: Characteristics of Mobilsol-30

| | |
|---|---|
| Percent Asphaltenes* | 0 |
| Percent Polar Compounds* | 8 |
| Percent Aromatics* | 79 |
| Percent Saturates* | 13 |
| Percent Residue in Emulsified Form | 66.7 |
| Flash Point*, °F | 505 |
| Kinematic Viscosity* at 140°F, c.st. | 164 |
| Specific Gravity* | 0.974 |

* Properties of Residue

Note: Constituents were obtained using Clay-Gel Analysis (ASTM D2007-75)

Table 2.6: Characteristics of AC-20

| Test | Value |
|---|---|
| Penetration, 100 gm, 5 sec., 77 $^{o}$F, 0.1 mm | 65 |
| Absolute Viscosity, 140 $^{o}$F, Poise | 1890 |
| Softening Point, $^{o}$F | 122 |
| Ductility, 77 $^{o}$F, 5cm/min., Cm | 150 + |

Bituminous Laboratory and has been used in many research projects.

## 2.2. Equipment

The major pieces of equipment used in this study include the resilient modulus test equipment, Hveem stabilometer and compression machine, Marshall testing equipment, pulse velocity test equipment and the high pressure-gel permeation chromatograph (HP-GPC). They are described in the following sections. Tests procedures are not included herein, but they are presented in later chapters relevant to their usages.

### 2.2.1. Resilient Modulus Test Equipment

The resilient modulus test equipment used in this study consists mainly of a load cell, specimen restraint, diaphragm air cylinder, source of compressed air, solenoid valve system, two transducers and control panel. The compressed air source is connected to the diaphragm air cylinder through the solenoid valve system. The solenoid valve is electrically activated and turned on for a duration of 0.1 seconds every 3 seconds, causing a pulse of compressed air to pass through the air cylinder and create a pulse load along the vertical diameter of the test specimen. The arrangement of this equipment is shown in Figure 2.1.

The magnitude of the pulse load is controlled through the adjustment of the compressed air. The horizontal deformation of the specimen is measured by the two transducers which are adjusted to lie on opposite sides of the horizontal diameter of the specimen as illustrated in Figure 2.1. The magnitude of the load and the resultant deformation are displayed on a detector on the electronic control panel. They can be read easily and recorded.

### 2.2.2. Hveem Stabilometer and Compression Machine

The Hveem stabilometer is a triaxial testing device used to determine the stability of compacted bituminous mixtures. It measures the horizontal pressure developed by a test specimen as a standard vertical pressure is applied. Figure 2.2 shows the Hveem stabilometer and the compression machine used for applying the vertical pressure. The compression machine is capable of applying pressures at constant preadjusted head speeds. For the stability measurement this speed is 0.05 inch per minute as required by the ASTM standards for the Hveem test.

### 2.2.3. Marshall Testing Equipment

The autographic Marshall testing apparatus shown in Figure 2.3 was used to conduct the Marshall stability tests on the recycled mixtures. A recorder provides a continuous load-deformation plot as a specimen is being loaded to failure.

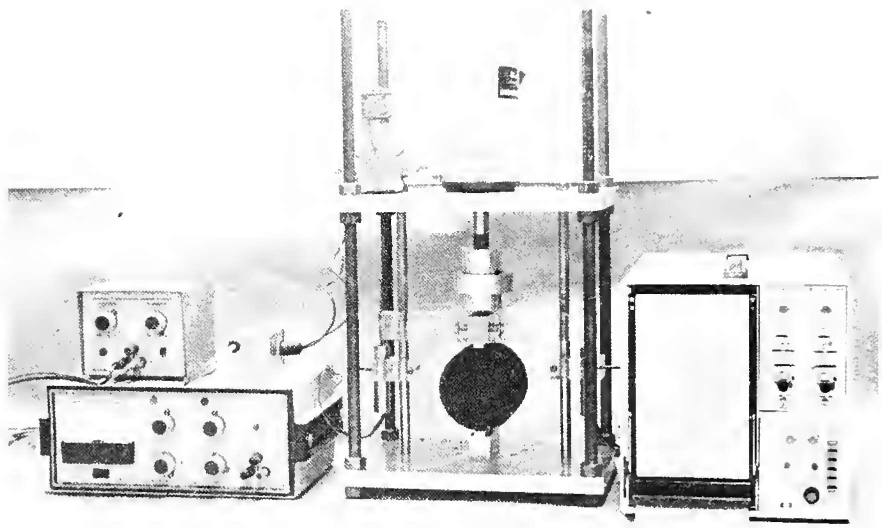


Figure 2.1 Resilient Modulus Equipment

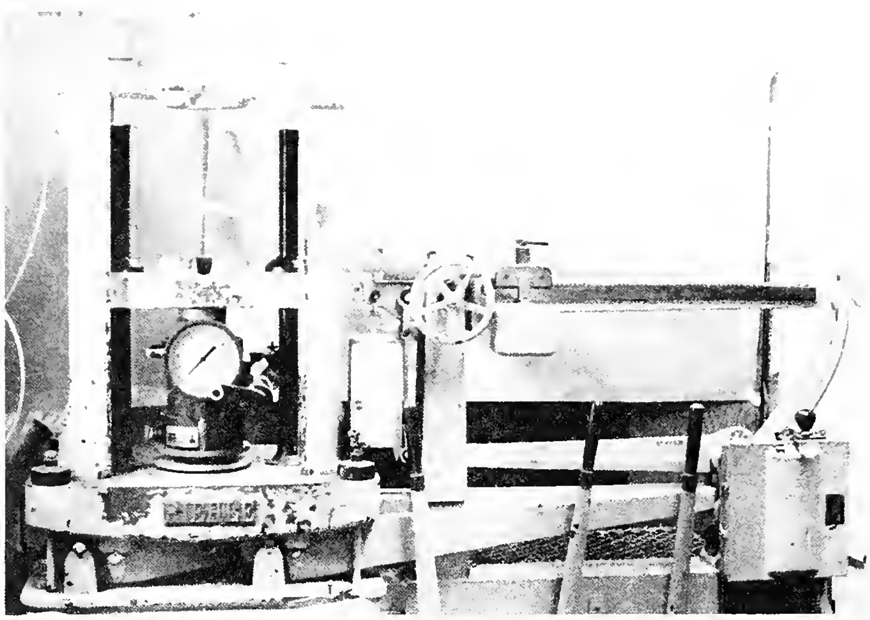


Figure 2.2 Hveem Stabilometer in the Compression Machine

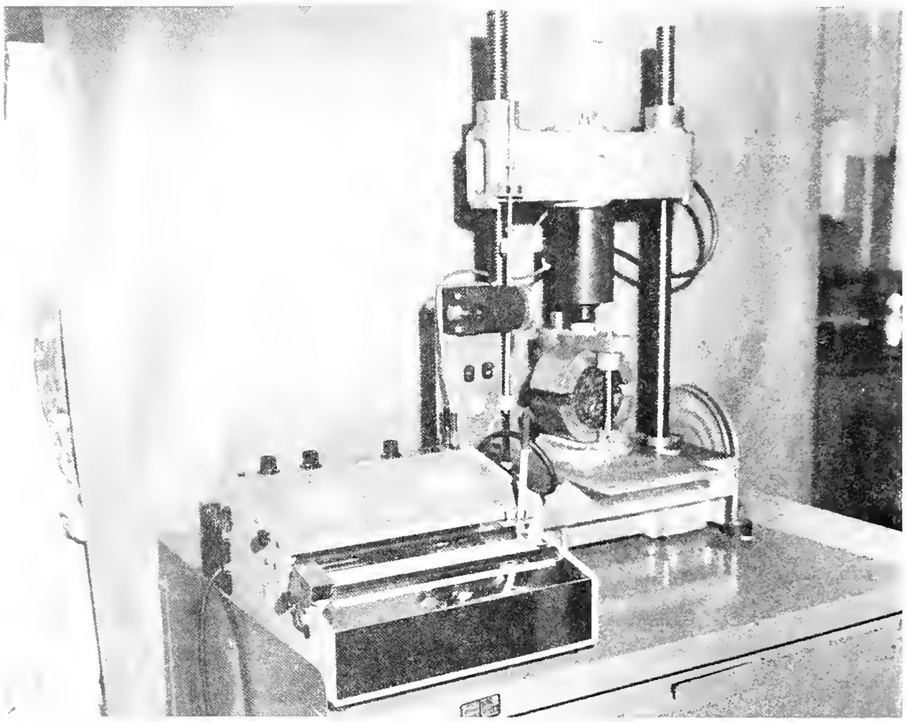


Figure 2.3 Marshall Testing Equipment

Load at failure is the specimen stability while total deformation at failure is its flow in units of 0.01 inch.

Marshall apparatus may also be used in determining the indirect tensile strength by using two opposite 0.5 inch wide strips on both top and bottom of specimen, as shown in Figure 2.4, instead of using the diametral loading frame used for stability test. The same Marshall type specimen can be used together with the same loading rate (2 inches per minute).

### 2.2.4. Pulse Velocity Test Equipment

The pulse velocity test equipment used in this study is the same as that required in the standard test on rocks, ASTM D 2845. It briefly consists of a sample holder (Marshall type specimen can be used), two transducers and a pulse generator with a timing unit.

The transducers are to be connected to the transmitter and receiver nodes of the pulse generator. The pulse generator sends mechanical pulses through the transducer connected to the transmitter node. The mechanical pulses passes through the sample and is received by the transducer connected to the receiver. The time required for the wave to pass through the sample is displayed on the timing unit screen and can be read easily and recorded. A general view of this arrangement is shown in Figure 2.5. The sample height divided by the time measured is the pulse velocity.

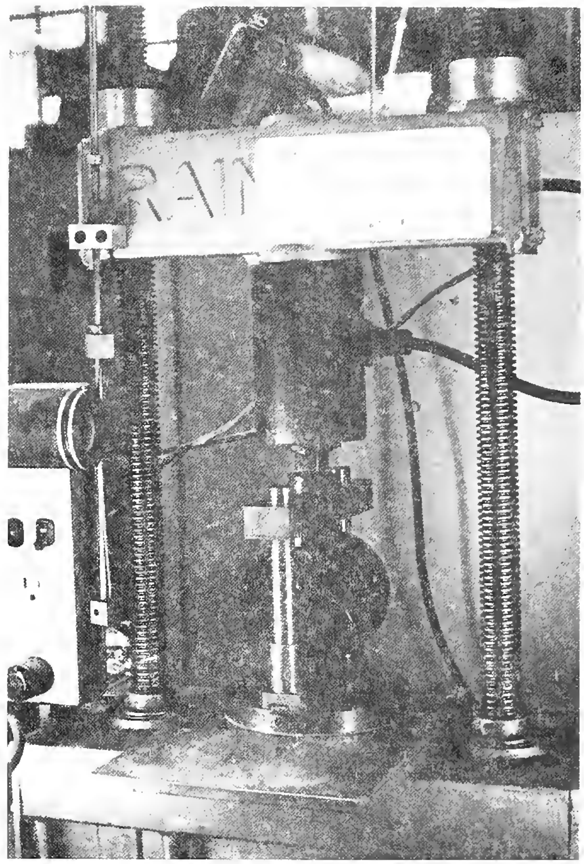


Figure 2.4 Indirect Tensile Testing Equipment

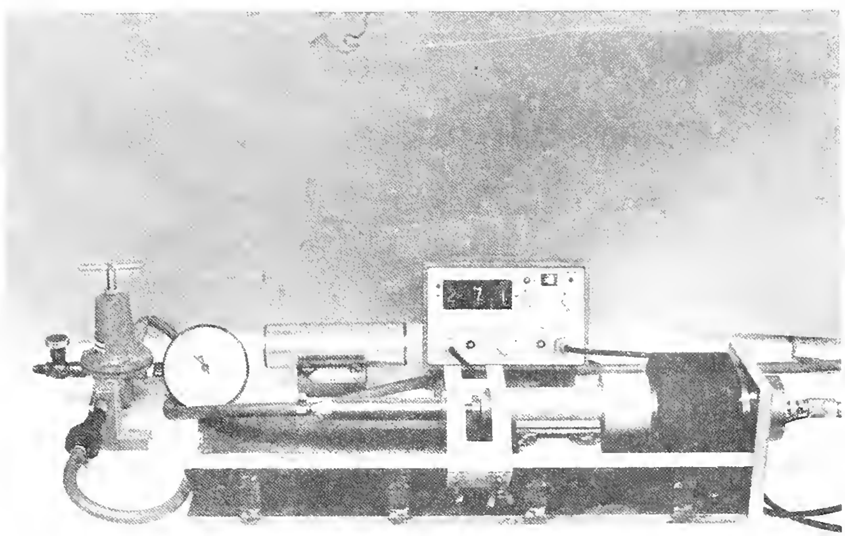


Figure 2.5 Pulse Velocity Equipment

# CHAPTER 3

# REJUVENATOR DIFFUSION IN OLD BINDER FILM

## 3.1. Determination of the Amount of Rejuvenator

Asphalt Institute curves (80) were used to determine an initial value for the percentage of rejuvenator (AC-2.5 and AE-150) to be added to the old binder to restore the properties to AC-20 range of classification. The AC-20 classification range was a target for its wide usage in producing high quality hot mix paving mixtures in the state of Indiana. The curves suggest the rejuvenator percentage based on its viscosity at 140°F, the old binder viscosity at 140°F and the required viscosity for the new rejuvenated binder at 140°F. The initial value for the percentage of Mobilsol-30 was chosen based on previous recycling projects (71, 81).

A series of extraction and recovery tests were conducted to justify these initial values. Table 3.1 shows the characteristics of salvaged asphalt, the rejuvenators and the three rejuvenated binders, together with the amount of rejuvenator being used. The values given are averages of ten samples.

## 3.2. The Concept of Stage Extraction

A stage extraction technique was used to determine the

Table 3.1: Characteristics of Salvaged Asphalt, Rejuvenators and Rejuvenated Binders

| Binder | Penetration | Vis. 140°F, Poises |
|---|---|---|
| Old Asphalt | 28 | 20,888 |
| AC-2.5 | 200 | 292 |
| AE-150 Residue | 200 | 270 |
| 40% Old Asphalt +60% AC-2.5 | 62 | 2112 |
| 45% Old Asphalt +55% AE-150 Residue | 68 | 1994 |
| 85% Old Asphalt 15% Mobilsol-30 Residue | 69 | 1974 |
| AC-20 spec. | 60+ | 1600-2400 |

Note: Mobilsol-30 characteristics are given in Table 3.5.

extent to which the salvaged bitumen will be softened by the recycling agent during the laboratory simulated hot mixing operation. The method used (explained later in detail) divides the asphalt binder film coating the aggregate into 4 successively extracted fractions. Each fraction is then characterized separately to determine how much it is affected by the rejuvenator or in other words to what extent did the rejuvenator diffuse into the old asphalt binder and affect its properties. The same technique was used to investigate the consistency distribution of the binder around the aggregate under 3 conditions; (1) the extracted mix containing RAP only, (2) the extracted mix containing RAP and a rejuvenator and (3) the extracted mix containing RAP, virgin aggregate and a rejuvenator.

## 3.3. Method

The recycled asphalt pavement (RAP) sample was heated in an oven at $240^{o}F$ for one hour. The rejuvenators; AC-2.5, AE-150 and the Mobilsol-30 were heated in an oven at ($180^{o}F$). The RAP, virgin aggregate and one of the rejuvenators were mechanically hot mixed for 2 minutes to ensure proper mixing. The loose samples were stored in an oven for 15 hours at $140^{o}F$ and directly extracted at different stages using Method A (ASTM D 2172). 1400 ml of Trichloroethylene solvent (TCE) were used to fully extract the binder from a

1200 gm sample of RAP. Seven samples were used to obtain the proper amount of recovered asphalt for each fraction for characterization. The solvent was applied to the mix in increments of; 200 ml, 200 ml, 300 ml and 700 ml respectively to have the extracted asphalt in four components. A five minute soaking period was required between the successive increments. Asphalt binder was then recovered separately from each of the four fractions by using Abson Method (ASTM D 1856) and characterized by means of penetration and viscosity tests. For those mixes that called for the addition of virgin aggregate, the aggregate was heated at 240$^{o}$F for 2 hours before mechanically mixing it with the RAP and the rejuvenator. The 200 ml of TCE was the minimum amount required to completely submerge the asphalt specimen in solvent. Last extracted component obtained by using 700 ml of TCE was a combination of 200 ml, 200 ml and 300 ml of TCE increments. In addition, the 5 minute soaking period was selected arbitrarily to be repeated for all asphalt samples and to provide information to repeat and check test results. For those cases where the amount of extracted asphalt was not sufficient to test by the standard penetration test, asphalt sample was tested for penetration in a 35 ml glass container and then tested by the standard absolute viscosity test.

## 3.4. Results of Fractional or Stage Extraction Process

### (1) RAP Only

The recycled asphalt pavement (RAP), without the addition of either virgin aggregate or recycling agent, was stage extracted for comparison purposes. The stage extraction process gave rise to some very interesting results. Table 3.2 shows the penetration and viscosity (140$^{\circ}$F) values of the reclaimed stage extracted old binder. Knowing that the original asphalt used was AC-20, it can be observed that the first component of the asphalt was severely hardened obviously due to direct exposure to weathering actions. However, the second component was less hardened and the third one was almost unchanged (compared to original AC-20 characteristics). On the other hand, the last component at the binder-aggregate interface was slightly hardened probably due to the tendency of limestone (commonly used in Indiana) to absorb light fractions of the binder. Figure 3.1 shows a schematic diagram for these four components together with the penetration and viscosity distribution along the old asphalt film.

### (2) Rejuvenator Effect, No Virgin Aggregate

It was decided in this portion of the study not to add any virgin aggregate in order to clarify the rejuvenator effect on old binder during the laboratory simulated hot mix operation. Table 3.3 shows the penetration and viscosity (140$^{\circ}$F) values of reclaimed stage extracted treated binder.

Table 3.2: Test Results on Reclaimed Stage Extracted RAP

| TCE Increment | Binder % By Weight | Penetration | Viscosity 140°F, Poise |
|---|---|---|---|
| 200 ml | 55.5 | 24 | 24,000 |
| 200 ml | 26.5 | 33 | 15,000 |
| 300 ml | 11.2 | 65 | 2,500 |
| 700 ml | 6.8 | 57 | 3,300 |

Notes: 1. Percent Asphalt Cement is 6% by weight of mix.

2. Original Asphalt used was AC-20.

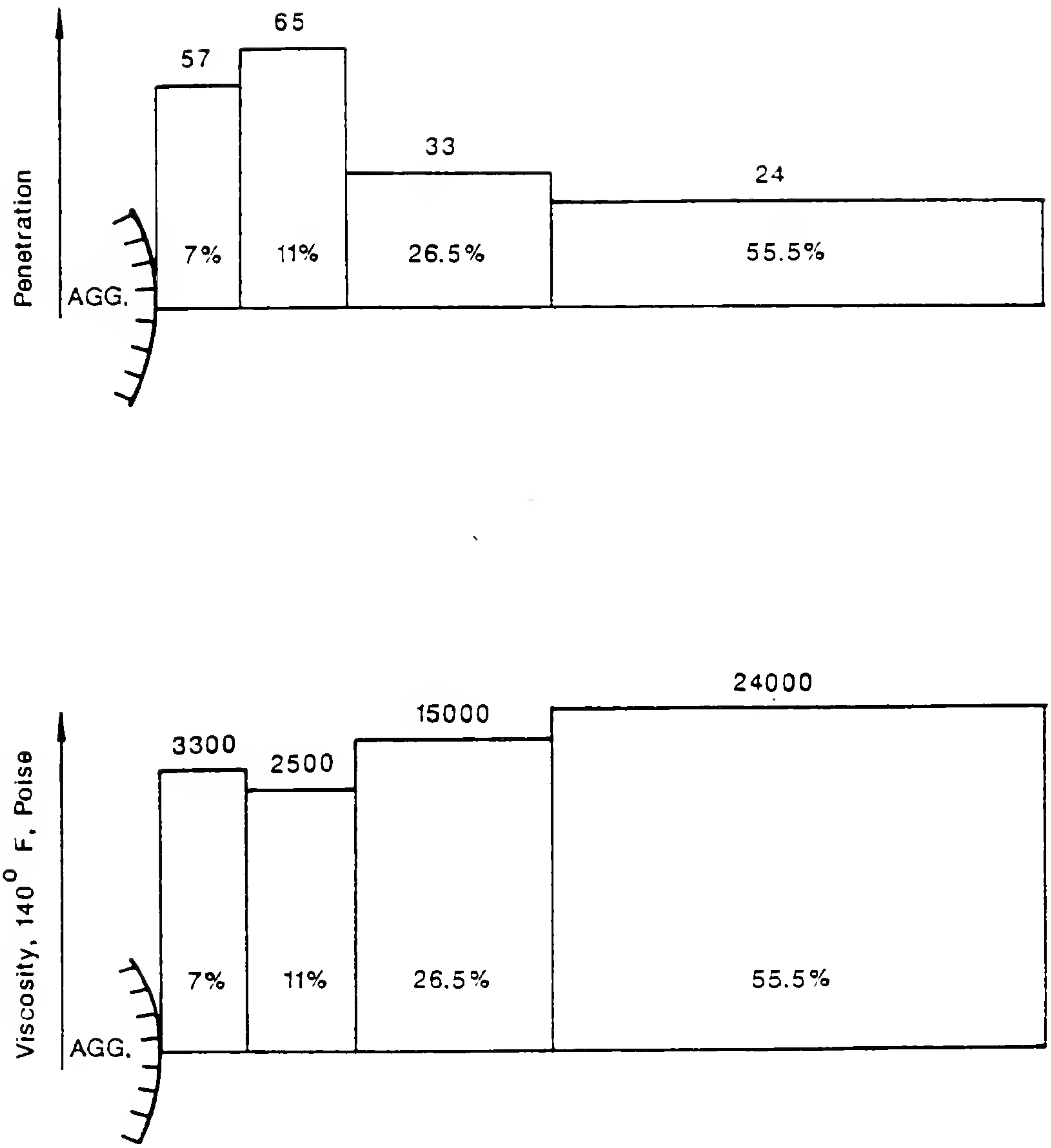



Figure 3.1 Consistency Distribution Throughout the Binder Film, RAP Only

Table 3.3: Test Results on Reclaimed Stage Extracted Treated Binders, No Virgin Aggregate

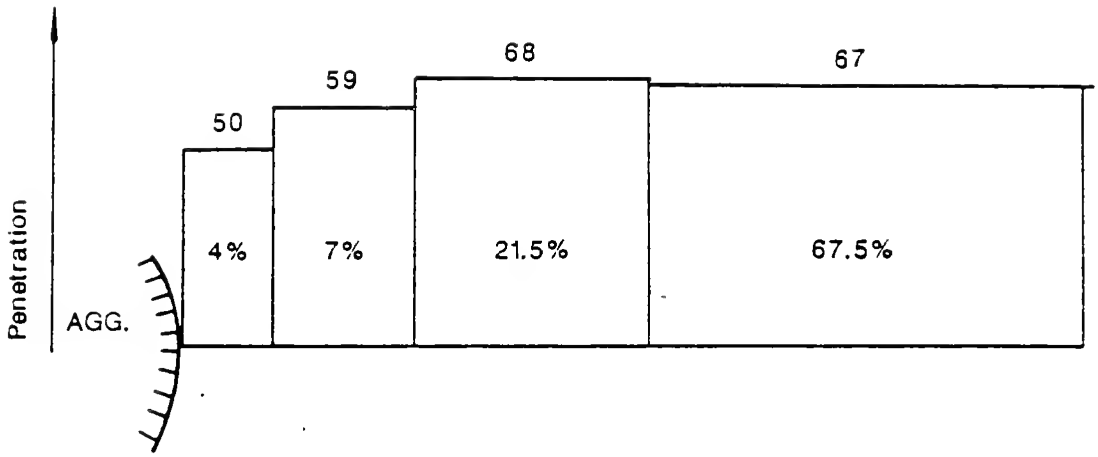
| Binder | TCE Increment | Binder % By Weight | Penetration | Viscosity 140°F, Poise |
|---|---|---|---|---|
| 60% AC-2.5 | 200 ml | 67.5% | 67 | 1674 |
| 40% Old Asphalt | 200 ml | 21.5% | 68 | 1880 |
| | 300 ml | 7% | 59 | 2394 |
| | 700 ml | 4% | 50 | 3000 |
| 55% AE-150 Residue | 200 ml | 69% | 75 | 1683 |
| 45% Old Asphalt | 200 ml | 16.5% | 70 | 2010 |
| | 300 ml | 8.5% | 62 | 2290 |
| | 700 ml | 6% | 49 | 3020 |
| 15% Mobilsol-30 Residue | 200 ml | 72% | 75 | 1864 |
| 85% Old Asphalt | 200 ml | 18% | 69 | 1980 |
| | 300 ml | 6% | 63 | 2040 |
| | 700 mll | 4% | 48 | 3152 |

Notes:
1. It was not possible to keep the percentage of treated binder at 6% (original percentage in RAP) since no virgin aggregate was added.
2. Treated binder contents by weight of mix were 13.75%, 12.5% and 7% for the AC-2.5, AE-150 and Mobilsol-30 respectively.

The results suggest that the three rejuvenators used (AC-2.5, AE-150 and Mobilsol-30) have almost identically restored the two outer layers of the old binder to the AC-20 range of specification while the other two inner layers were almost unaffected. However these two layers were not significantly hardened as previously indicated by the results of stage extracting the RAP only. Figures 3.2 through 3.4 show a schematic diagram for the four layers together with the penetration and viscosity distributions along the treated asphalt film.

(3) Rejuvenator Effect in Combination with Virgin Aggregate

Since the hot mix recycling operation generally requires the use of virgin aggregate, it was imperative to include the rejuvenators effect on old binder in the existence of virgin aggregate. The amount and gradation of aggregate added was selected to keep the treated binder content at 6% by weight of mix (same as binder content in RAP) and the total aggregate fraction gradation within the #12 surface range of specification which is commonly used in Indiana for producing hot mix bituminous pavement. These two requirements were met by using virgin aggregate percentages of 60%, 55% and 15% by total aggregate weight for the mixes treated with AC-2.5, AE-150 and Mobilsol-30 respectively. The gradation used was the specification mid point of #12



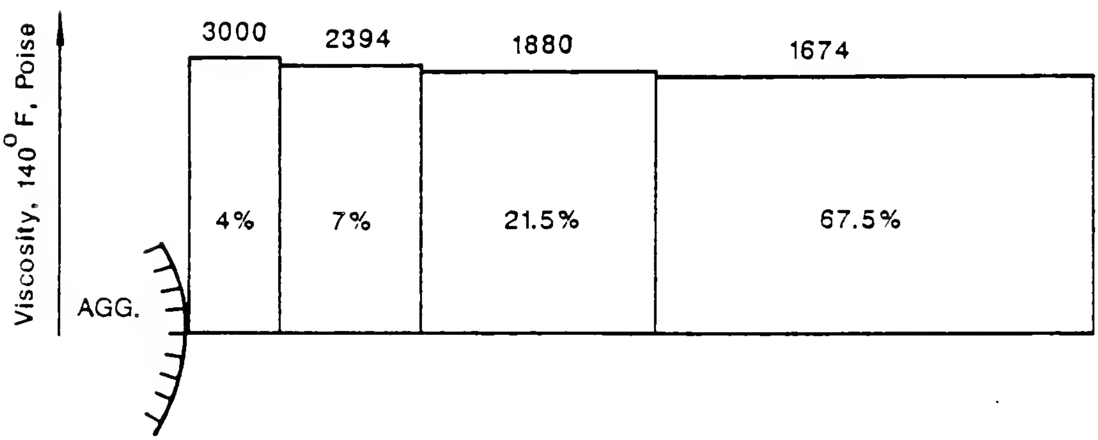
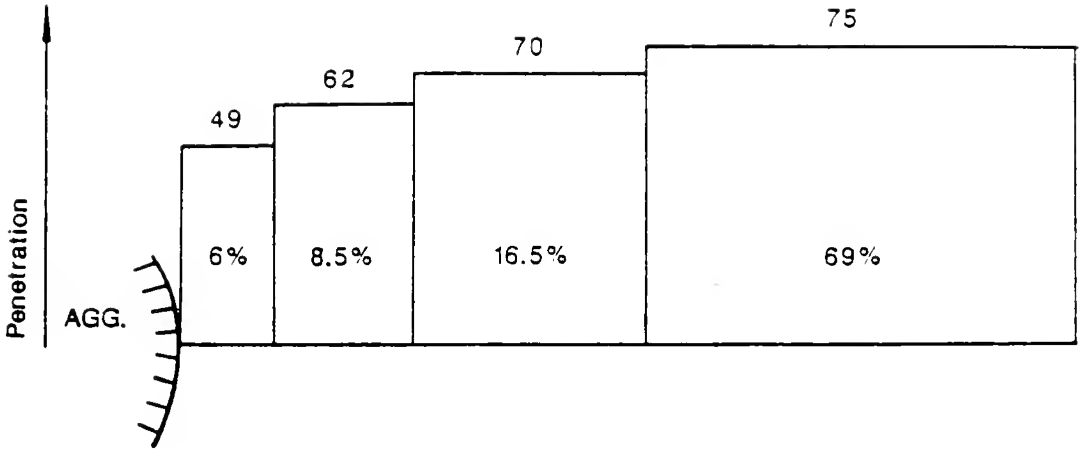




Figure 3.2 Consistency Distribution Throughout the Binder Film, (RAP + AC - 2.5), No Virgin Aggregate.



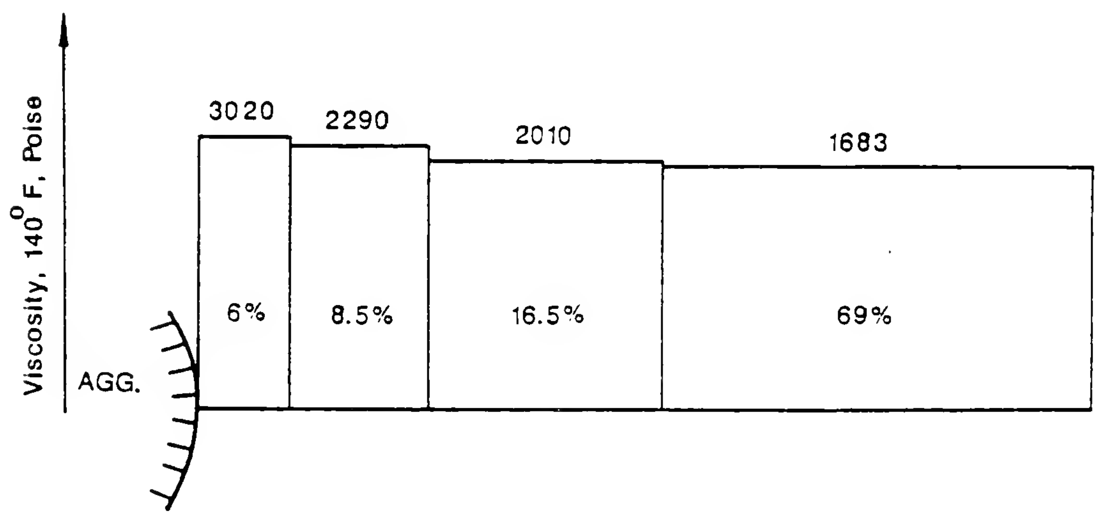
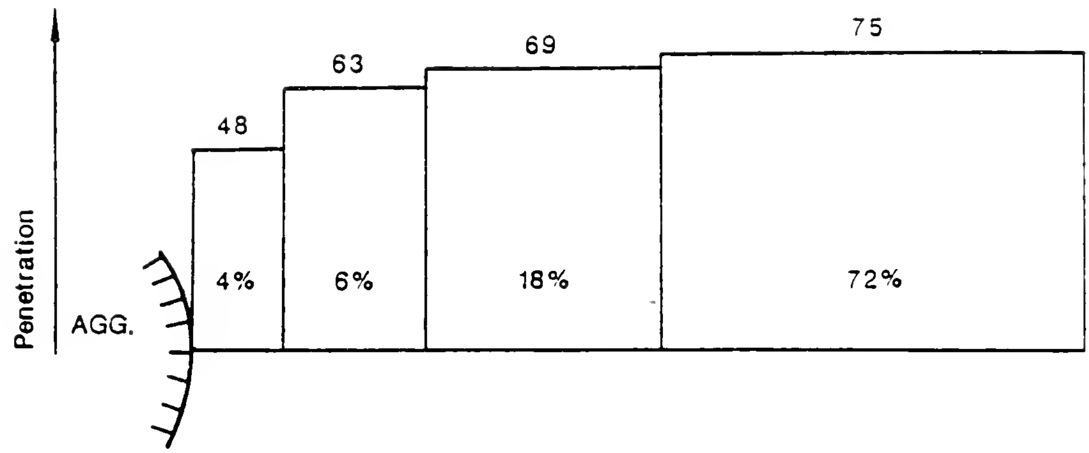




Figure 3.3 Consistency Distribution Throughout the Binder Film, (RAP + AE - 150), No Virgin Aggregate.



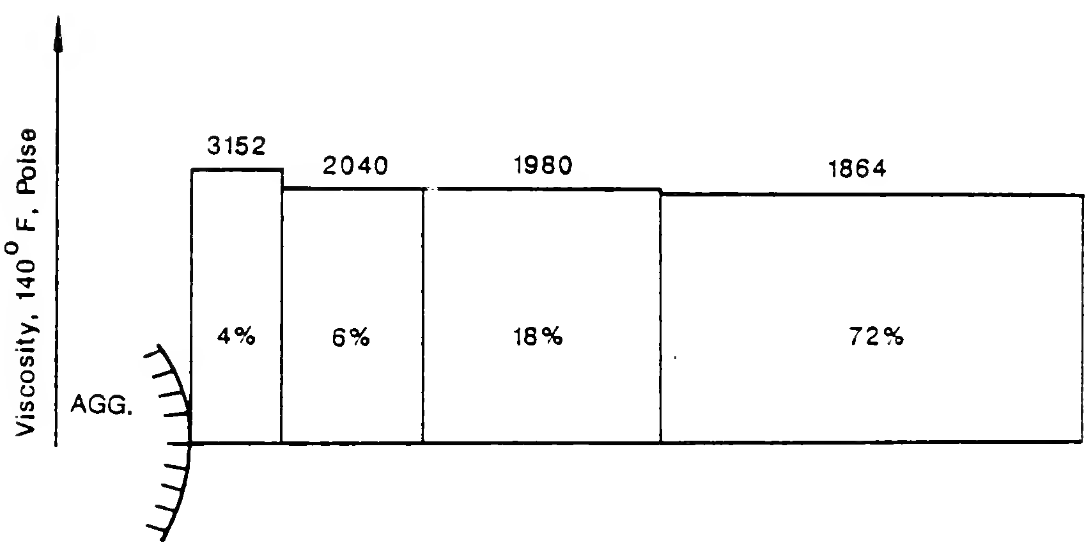




Figure 3.4 Consistency Distribution Throughout the Binder Film, (RAP + Mobilsol - 30), No Virgin Aggregate.

surface shown previously in Table 2.2. The heated rejuvenators (AC-2.5, AE-150 or Mobilsol-30) were added during the mixing of the heated virgin aggregate - RAP combination. Table 3.4 presents the penetration and viscosity (140$^{\circ}$F) values of the reclaimed stage extracted binder. The results suggest that both rejuvenators (the AC-2.5 and the Mobilsol-30) probably were first attracted to the old asphalt binder, softened it and then covered the virgin aggregate as reflected by low viscosity and large penetration values obtained for the last component. However, this was not the case for the AE-150 where its results indicated almost an identical consistency gradient to the one with no virgin aggregate. Last extracted component displayed penetration and viscosity values similar to those with no virgin aggregate.

In general, the consistency of the four microlayers of the treated binder (representing the whole film of asphalt coating the aggregate) characterized by the penetration and viscosity (at 140$^{\circ}$F) results was similar to that of AC-20 indicating good efficiency for the rejuvenators (AC-2.5, AE-150 and Mobilsol-30) in diffusing through the hard asphalt film and restoring its properties to the AC-20 specification range. Figures 3.5 through 3.7 present a schematic diagram for the four layers together with the penetration and viscosity distributions along the treated asphalt film.

Table 3.4: Test Results on Reclaimed Stage Extracted Treated Binders, Virgin Aggregate Were Used

| Binder | TCE Increment | Binder % By Weight | Penetration | Viscosity 140°F |
|---|---|---|---|---|
| * 60% AC-2.5 | 200 ml | 72 | 60 | 2,100 |
| * 40% Old Asphalt | 200 ml | 19 | 51 | 2,892 |
| | 300 ml | 5.5 | 52 | 2,470 |
| | 700 ml | 3.5 | 130 | 809 |
| *55% AE-150 Residue | 200 ml | 71 | 70 | 1,972 |
| | 200 ml | 19 | 67 | 1,734 |
| #45% Old Asphalt | 300 ml | 6 | 60 | 2,424 |
| | 700 ml | 4 | 50 | 3,616 |
| *15% Mobilsol-30 | 200 ml | 74 | 73 | 2,049 |
| Residue | 200 ml | 17.5 | 80 | 1,664 |
| *85% Old Asphalt | 300 ml | 5.5 | 90 | 1,260 |
| | 700 ml | 3.5 | 100 | 1,240 |

Note: *Percent Binder was 6% for all mixes.

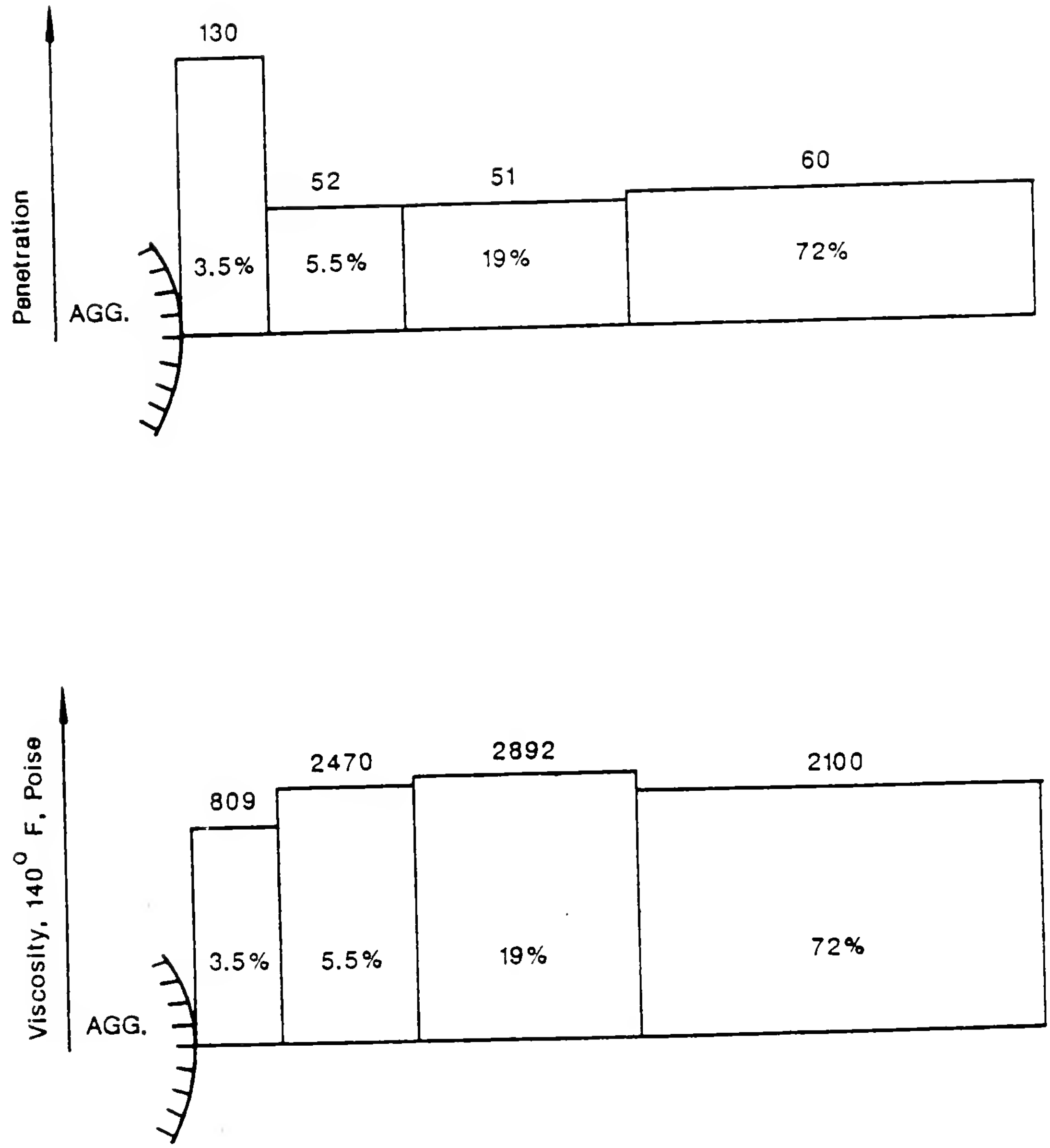
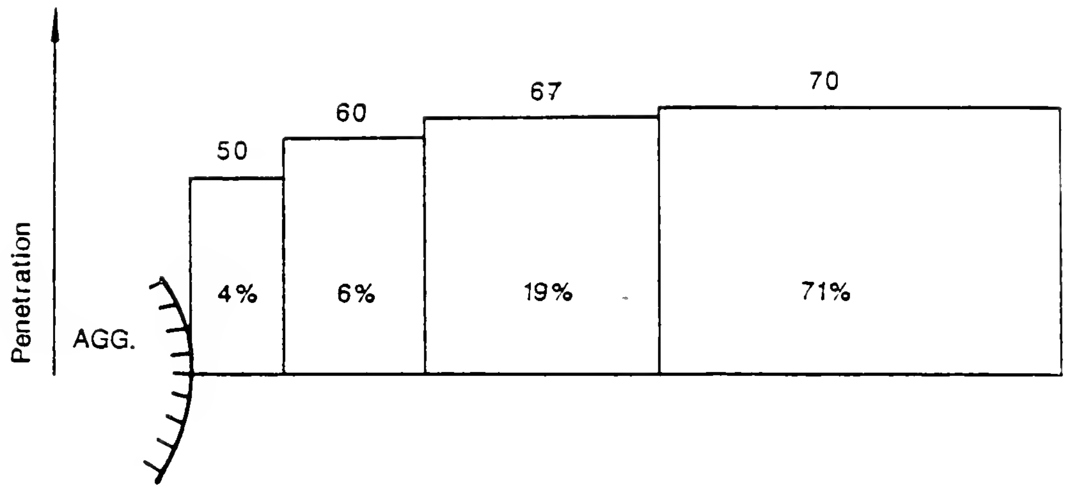



Figure 3.5 Consistency Distribution Throughout the Binder Film, (RAP + AC - 2.5) in Combination With Virgin Aggregate.



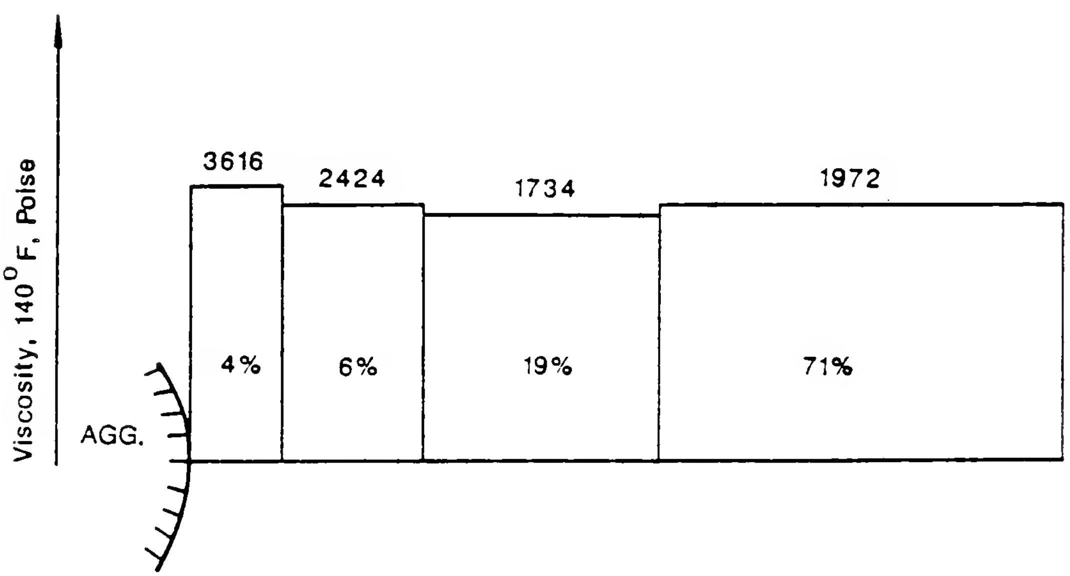




Figure 3.6 Consistency Distribution Throughout the Binder Film, (RAP + AE - 150) in Combination With Virgin Aggregate.

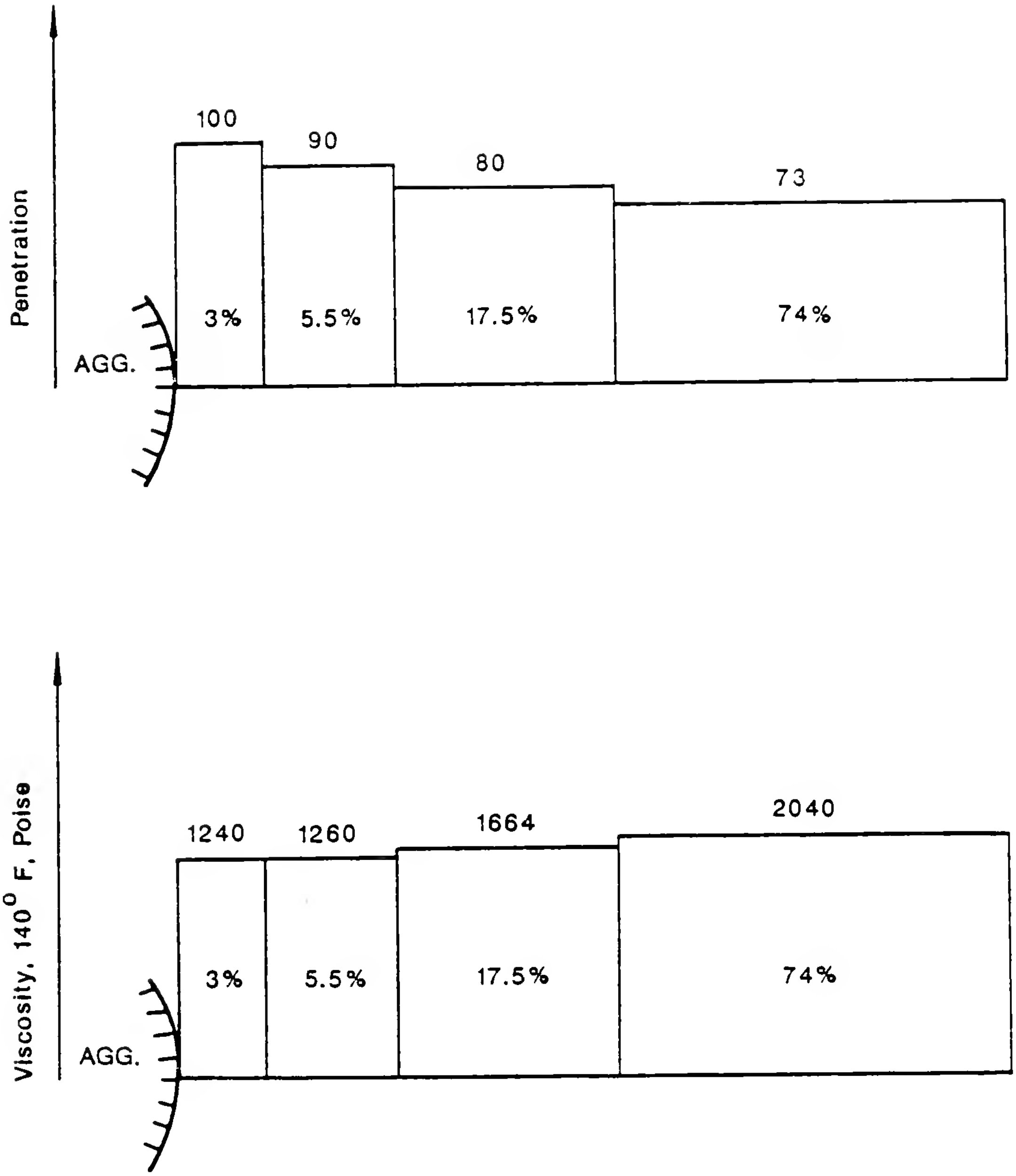



Figure 3.7 Consistency Distribution Throughout the Binder Film, (RAP + Mobilsol - 30) in Combination With Virgin Aggregate.

## 3.5. Development of Microlayers and Theoretical Implications

It has been observed that the penetration and viscosity (at 140°F) values for the four microlayers of asphalt film extracted and reclaimed for all samples used in this study are logarithmically additive. In other words if $Log_{10}A$, $Log_{10}B$, and $Log_{10}C$ and $Log_{10}D$ represent the logarithmic values for the penetration or the viscosity (140°F) of the four microlayers and $Log_{10}T$ represent that value for the whole asphalt film, it was observed that:

$$Log_{10}T = P1\ Log_{10}A + P2\ Log_{10}B + P3Log_{10}C + P4Log_{10}D$$

where P1, P2, P3 and P4 are the weight percentages of the four microlayers. Taking the RAP rejuvenated by Mobilsol-30 as an example: $P_1$, $P_2$, $P_3$ and $P_4$ are 0.72, 0.18, 0.06, 0.04 (Table 3.3 and A, B, C and D viscosity values are 1864, 1980, 2040 and 3152 poises (Table 3.3). Substituting these values in the above equation, T is 1935 which is reasonably close to its test value, 1974 (Table 3.1).

Since the proof of this relationship would entail a research effort that is beyond the magnitude of this study, it was necessary to include it only as an observation. However, this relationship can be used to develop the results for the four microlayers obtained in this study into 10 microlayers

or more. Figures 3.8 and 3.9 illustrate the relationship between the percent binder extracted and the penetration or the viscosity ($140^{\circ}F$) of the extracted old binder (RAP) and the RAP treated with AC-2.5, AE-150 and Mobilsol-30 for the case of using virgin aggregate. It would be possible to predict the penetration or viscosity value of the last 5% microlayer (at binder-aggregate interface) by obtaining the viscosity or penetration value at 95% (A) binder extracted and at 100% binder extracted (T) and substituting them in the above relationship. Taking the untreated RAP as an example; the "A" penetration value is 27 at 95% binder extracted (Figure 3.8) and the "T" penetration value at 100% binder extracted is 28 (Figure 3.8). $P_1$ and $P_2$ are 0.95 and 0.05. Substituting these values in the above equation, "B" penetration value is 56 which is close to the test value shown in Table 3.2 (57).

### 3.6. Summary of Results

The main findings of this part of the study can be summarized as follows:

1. Stage extraction of the hard asphalt film for the recycled asphalt pavement (RAP) indicated a non uniform consistency distribution. The first component of the binder was severely hardened obviously due to direct exposure of weathering actions. However, the second

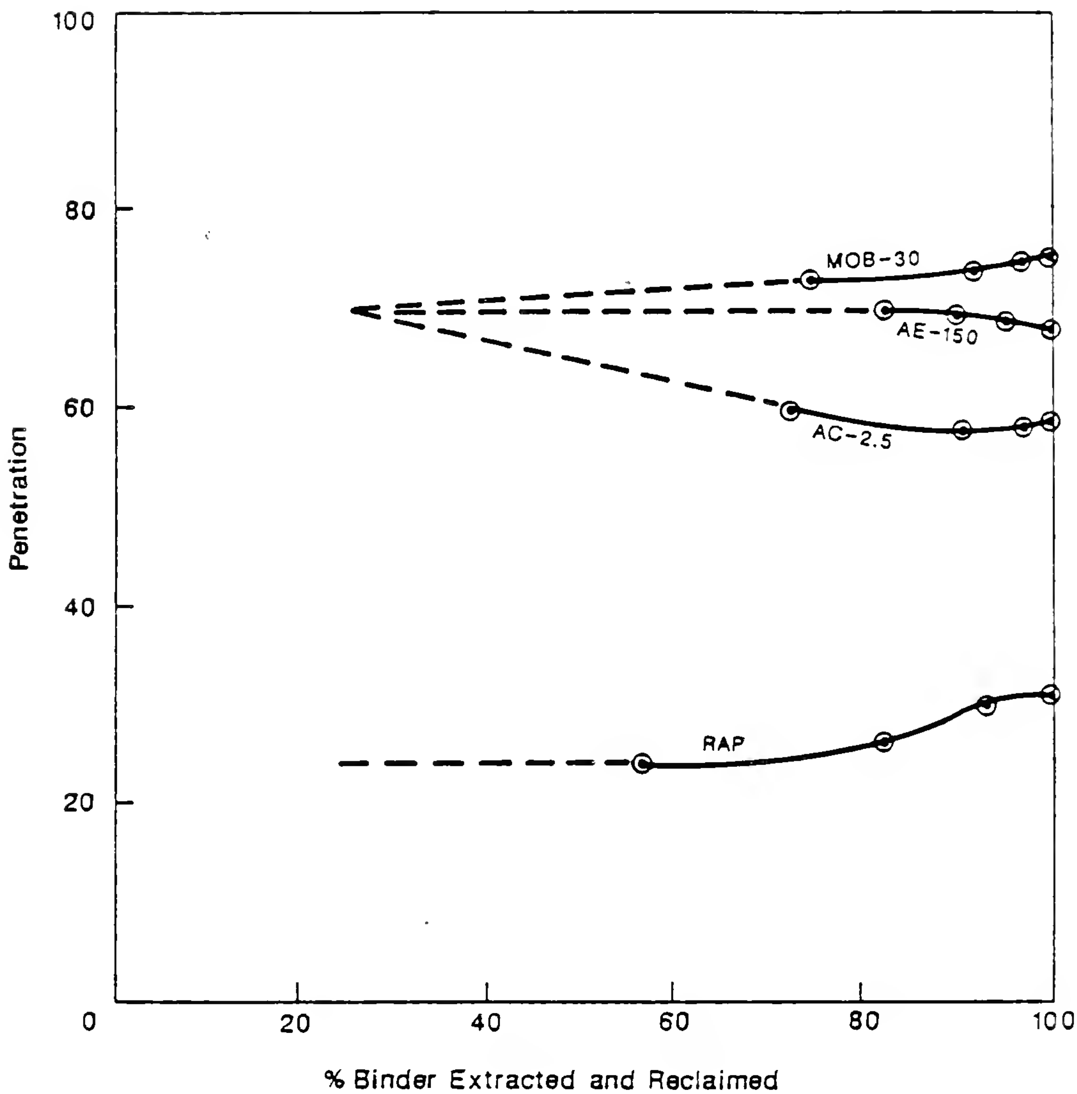



Figure 3.8 Relationship Between Percent Binder Extracted and Reclaimed and Penetration, (Virgin Aggregate was used).

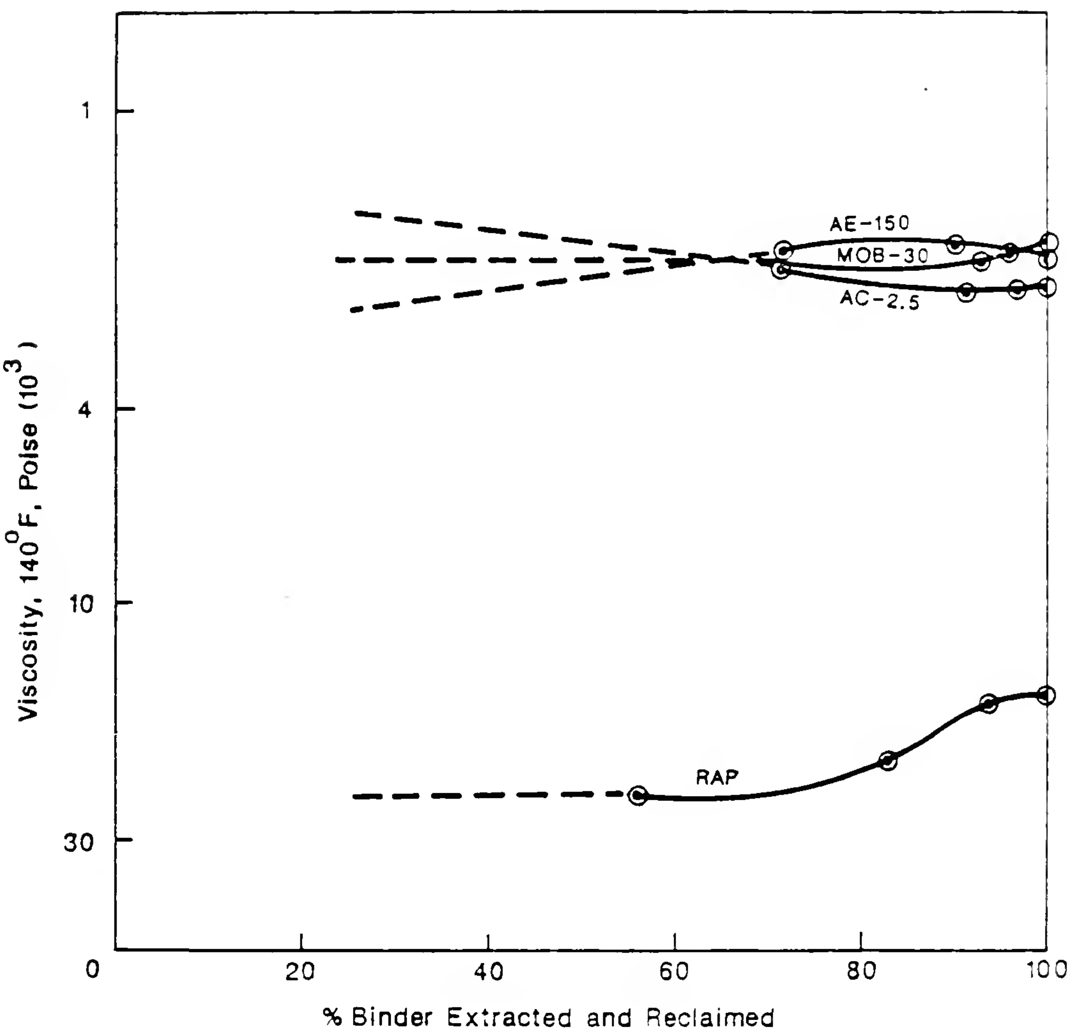



Figure 3.9 Relationship Between Percent Binder Extracted and Reclaimed and Absolute Viscosity, (Virgin Aggregate was used).

component was less hardened and the third component seems to retain its original consistency at time of construction. The slight hardening of the last component (at asphalt aggregate interface) may be due to tendency of limestone (commonly used in Indiana) to absorb light fractions.

2. Stage extraction of the binder rejuvenated by AC-2.5, AE-150 or Mobilsol-30 without the existence of virgin aggregate indicated that the rejuvenators are most effective at softening the hardened binder on the outer two microlayers of the asphalt film.

3. Stage extraction of rejuvenated binders in the presence of virgin aggregate indicated variable trends regarding the consistency distribution of asphalt film on the aggregate. The attraction of the low viscosity rapidly softened binder to the virgin aggregate may have been the cause of these inconsistent trends.

4. Generally all three rejuvenators were successful in restoring the old hardened asphalt film to the AC-20 specification range.

5. The three recycling agents used had displayed good efficiency in diffusing through the hard asphalt film as indicated by stage extraction test results after a period of time of 15 hours. Careful selection of a

recycling agent (rejuvenator) is essential in order to ensure good efficiency in its diffusion into the hard asphalt film of the RAP during a short period of time.

It should be important to indicate that the conclusions obtained from that portion of the study (stage extraction and microlayers) reflect a concept that might help understanding asphalt consistency characteristics present in RAP and may require more research to be considered a fact. First component of binder exposed to TCE is the first component that would be exposed to the rejuvenator in the rejuvenation process and most likely it was the portion more exposed to air in the field. Coated aggregate surrounded with air voids will be the first to be ripped apart in the laboratory. In addition, the stage extraction technique followed was initially based on the old concept (asphalt consistency in the RAP is uniformly hardened and recycling agent used may rejuvenate just a part of it leaving another part unrejuvenated, brittle and can be considered part of the aggregate) in a process to test the efficiency of recycling agents used and predict whether one is more efficient than the other. The research results, ever unpredictable, did not indicate significant differences in this regard but came out with some new concept. At the very least, it can be said that the above stated old concept is doubtful and asphalt present in RAP is not uniformly hardened.

# CHAPTER 4

# EVALUATION OF RECYCLED BINDER USING THE THIN FILM OVEN TEST

## 4.1. Preparation of Samples for the Thin Film Oven Test

The recycled asphalt pavement (RAP) samples were randomly selected and heated in an oven at 240°F for one hour. The characteristics of the salvaged binder and the gradation of salvaged aggregate are given previously in Tables 2.1 and 2.2 of Chapter 2.

The rejuvenators; AC-2.5, AE-150 and Mobilsol-30 were heated in an oven at 180°F when any of them were used (40% old binder + 60% AC-2.5), (45% old binder + 55% AE-150 residue) and (85% old binder + 15% Mobilsol-30) were the percentages used to produce 3 rejuvenated binders within the AC-20 range of specifications. These percentages were previously justified during the part of study presented in Chapter 3. The characteristics of the rejuvenators and the rejuvenated binders are given previously in Tables 2.3, 2.4, 2.5 and 3.1.

The virgin aggregate was heated in an oven at 240°F for two hours. The amount and gradation of virgin aggregate were selected in such a way that the resulting binder content by total weight of mix is 6% (original binder content in RAP) and the resulting aggregate gradation is within the Indiana

specification for #12 surface (typically used for producing hot mix bituminous surface mix). These two requirements were met by using virgin aggregate percentages of 60%, 55%, and 15% by total aggregate weight for mixes treated with AC-2.5, AE-150 and Mobilsol-30 respectively.

The gradation used was the specification midpoint of #12 surface shown previously in Table 2.2. The RAP, virgin aggregate and one of the rejuvenators were mechanically hot mixed for 2 minutes. The loose samples were stored in an oven for 15 hour at 140$^{o}$F for curing and directly extracted using Method A (ASTM D 2172). Asphalt binder were then recovered separately using Abson Method (ASTM D 1856).

Actual field conditions were simulated with the addition of virgin aggregate to the RAP followed by the rejuvenator except for the Mobilsol-30 where its addition was before the virgin aggregate. In other words, the salvaged binder was treated before the extraction and recovery process was conducted. Samples of virgin AC-20 were used for comparison purposes.

## 4.2. Results and Analysis of the Thin Film Oven Test

Penetration and viscosity values at 140$^{o}$F were obtained on recovered rejuvenated asphalt samples (zero time on TFOT) and on residues after 2 hours, 5 hours (the standard time) and 10 hours in the thin film oven. Identical conditions

were applied on AC-20 and its penetration and viscosity values at 140°F were obtained for comparison purposes.

Tables 4.1 and 4.2 give the average penetration and viscosity (at 140°F) values of the three replications at each treatment combination (binder type and time of oven exposure). Significant differences were obtained when conducting a two way analysis of variance (ANOVA) on the data (see Appendix A). The time of oven exposure resulted in a significant drop in the penetration and a significant increase in the viscosity for all the samples (which is expected). However these changes varied significantly depending on the binder type. The RAP rejuvenated by the AE-150 experienced the highest hardening rate followed by the virgin AC-20, the RAP rejuvenated by AC-2.5 and the RAP rejuvenated by the Mobilsol-30 respectively. In addition, after conducting the TFOT on samples of RAP rejuvenated by AE-150, an interesting phenomenon was observed. A brittle skin was formed on the top of the sample in the pan which could be easily removed. This was true for all the samples of RAP modified by AE-150 even those that were exposed for only 2 hours in the oven.

In general, it can be indicated that when using AE-150 as a recycling agent for hot mix recycled bituminous pavements, potential incompatibility, non-homogeneity and high rate of hardening problems may be expected. This may not be the

Table 4.1: Penetration Values of Binder After Different Times of Oven Exposure

| Binder Type | Time of Oven Exposure During TFOT: Zero | 2 Hours | 5 Hours | 10 Hours |
|---|---|---|---|---|
| AC-20 | 65 | 43 | 33 | 25 |
| RAP+AC-2.5 | 64 | 48 | 38 | 29 |
| RAP+AE-150 | 62 | 34 | 26 | 18 |
| RAP+Msol-30 | 64 | 50 | 43 | 33 |

Note: Values included are average of 3 replications.

Table 4.2: Viscosity Values (at 140$^{o}$F) of Binders After Different Times of Oven Exposure

| | Time of Oven Exposure During TFOT | | | |
|---|---|---|---|---|
| Binder Type | Zero | 2 Hours | 5 Hours | 10 Hours |
| AC-20 | 1890 | 3920 | 8780 | 25,870 |
| RAP+AC-2.5 | 1980 | 3410 | 7890 | 15,080 |
| RAP+AE-150 | 2150 | 9770 | 18,740 | 62,340 |
| RAP+Mobilsol-30 | 2220 | 4680 | 7490 | 14,880 |

Note: Values included are average of 3 replications.

case for the AC-2.5 or the Mobilsol-30 as their results encourage their usage as recycling agents. The RAP rejuvenated by either AC-2.5 or Mobilsol-30 indicated a hardening rate which is even slightly slower than that of the virgin AC-20.

## 4.3. Relationship Between the Time of Oven Exposure and Consistency of Binder

Regression analyses were conducted in order to establish statistical relationships between the time of oven exposure during the TFOT (zero, 2, 5 and 10 hours) and the consistency of binder (AC-20, RAP + AC-2.5, RAP + AE-150 or RAP + Mobilsol-30) represented by the penetration and the viscosity at 140$^{\circ}$F. Tables 4.3 and 4.4 illustrate these regression equations for penetration and viscosity respectively. The symbol "x" was used to represent the time spent in the thin film oven test. The regression parameter multiplied by "x" can be used as an indicator for the tendency of the rejuvenated binder to have high hardening rate and hence create short term aging and possible incompatibility and non-homogeneity problems.

Figures 4.1 and 4.2 demonstrate the graphical representations for these statistical relationships for both penetration and viscosity at 140$^{\circ}$F versus the time of oven exposure respectively.

Table 4.3: Regression Equations for the Relationship Between Penetration of Binder and Time of Oven Exposure During TFOT

| Binder Type | Equation | $R^2$ |
|---|---|---|
| AC-20 | $\text{Penetration} = \dfrac{100}{\sqrt{2.45+1.35x}}$ | 0.999 |
| RAP+AC-2.5 | $\text{Penetration} = \dfrac{100}{\sqrt{2.45+0.95x}}$ | 0.999 |
| RAP+AE-150 | $\text{Penetration} = \dfrac{100}{\sqrt{2.45+2.45x}}$ | 0.993 |
| RAP+Mobilsol-30 | $\text{Penetration} = \dfrac{100}{\sqrt{2.45+0.75x}}$ | 0.993 |

Notes: (1) "x" is the time of oven exposure during the TFOT.

(2) $R^2$ is the coefficient of determination.

Table 4.4: Regression Equations for the Relationship Between Viscosity (at 140°F) and Time of Oven Exposure During TFOT

| Binder Type | Equation | $R^2$ |
|---|---|---|
| AC-20 | Viscosity = $(45.4 + 10x)^2$ | 0.999 |
| RAP+AC-2.5 | Viscosity = $(45.4+9x)^2$ | 0.982 |
| RAP+AE=150 | Viscosity = $(45.4+22x)^2$ | 0.975 |
| RAP+Mobilsol-30 | Viscosity = $(45.4+8x)^2$ | 0.977 |

Notes: (1) "x" is the time of oven exposure during the TFOT.

(2) $R^2$ is the coefficient of determination.

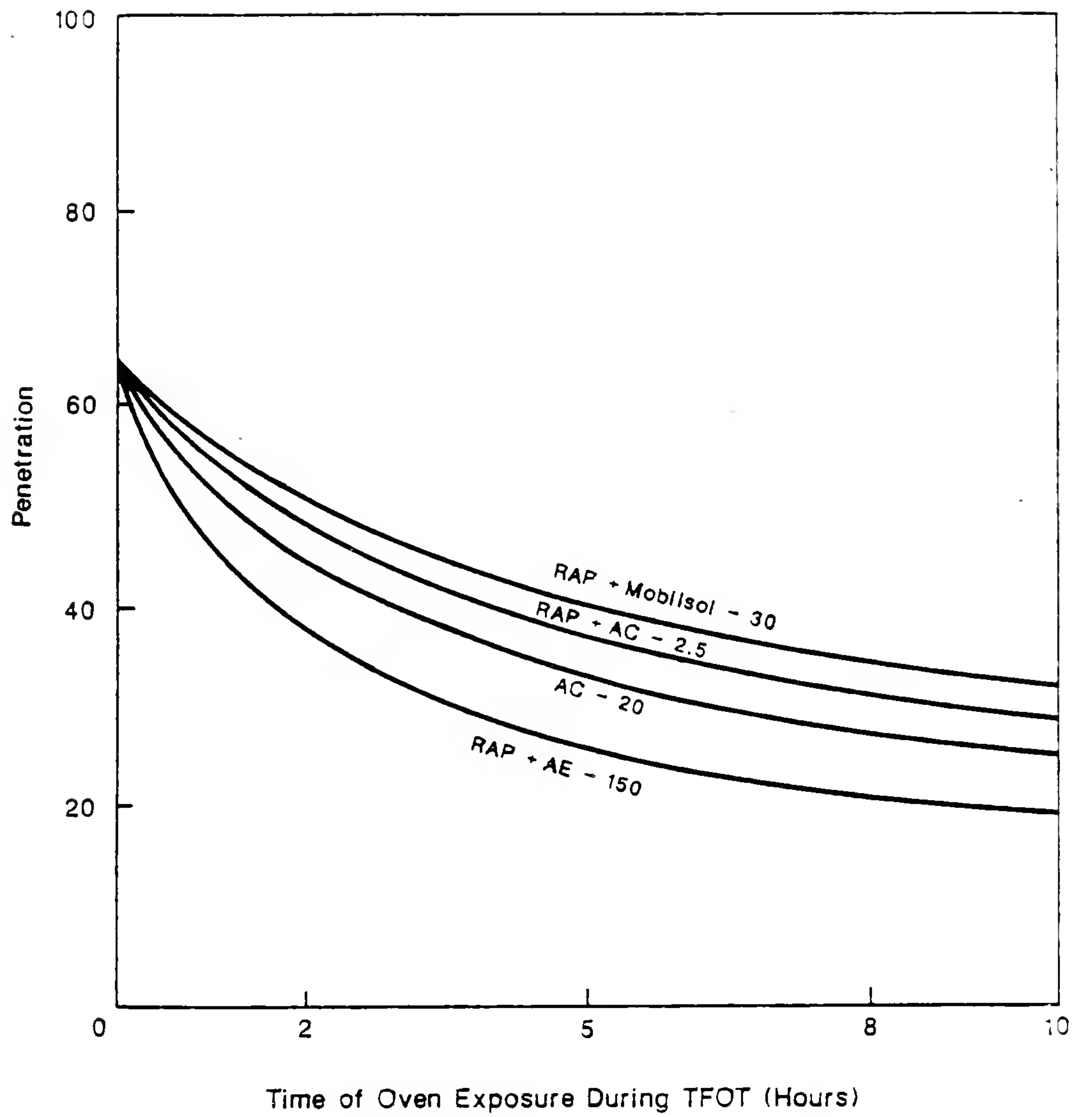



Figure 4.1 Relationship Between Penetration and Time of Oven Exposure During The Thin Film Oven Test

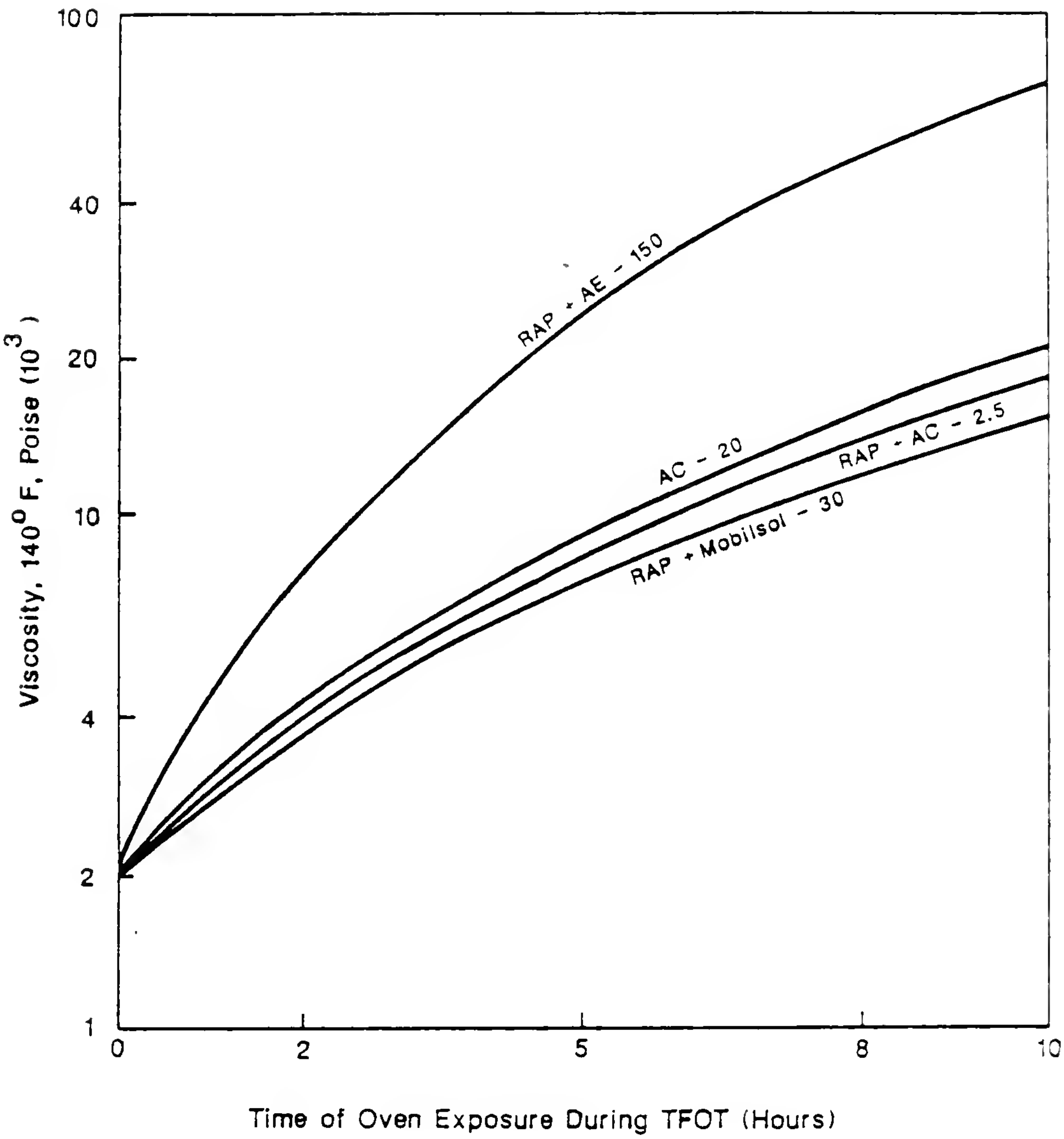



Figure 4 .2 Relationship Between Viscosity and Time of Oven Exposure During The Thin Film Oven Test

Regression equations are always condition dependent and may not be expanded for conditions other than those used in this study. Extrapolation in these equations may also be not appropriate. However, these equations shown in Table 4.3 can be used for documenting performance of widely used asphalt cements.

## 4.4. Summary of Results

The main conclusions can be summarized as follows:

1. Rejuvenated binders having the same consistency as a virgin binder may have different long term performances and hardening rates.

2. It is not enough to have a rejuvenated binder meeting the standard specifications for a virgin binder to assure the success of a hot-mix recycled pavement. Additional criteria and test conditions have to be developed for this assurance.

3. The thin film oven test was identified as a potential added criterion in identifying recycling agents that have more tendency of causing high rate of hardening, non-homogeneity and non-compatibility problems of recycled binders meeting the standard specifications of a virgin binder. It has been illustrated that this identification can be obtained by both visually

inspecting the residues after the thin film oven test and classifying their consistency using penetration and viscosity tests.

4. Salvaged asphalt existing in the RAP may experience a high rate of hardening and create non-homogeneity and non-compatibility problems in the hot mix recycled asphalt pavement if it was rejuvenated by the AE-150 as a recycling agent. However, this may not be the case when using the AC-2.5 or the Mobilsol-30 as recycling agents where their usage indicated a slightly slower hardening rate than the virgin AC-20.

5. An interesting feature was observed when using the AE-150 for treating the weathered asphalt. A brittle skin tended to form on all the thin film oven test residues and was easily separated from the rest of the sample.

6. Careful selection and testing of a recycling agent (rejuvenator) is essential in order to ensure good quality hot mix recycled asphalt pavement with an acceptable performance compared to a conventional pavement.

# CHAPTER 5

# TESTING PROGRAM TO EVALUATE COMPACTED HOT MIX RECYCLED ASPHALT PAVEMENT

Virgin mixtures containing virgin AC-20 and #12 surface virgin aggregate were compared against 3 other recycled mixtures. Salvaged binders present in recycled mixtures were restored to AC-20 range of classification by using (60% AC-2.5 + 40% old asphalt), (55% AE-150 + 45% old asphalt) and (85% Mobilsol-30 + 15% old asphalt). These percentages were previously justified during the study presented in Chapter 4. Salvaged-virgin aggregate combinations in recycled mixtures were adjusted to have the gradation of #12 surface. This adjustment was not complicated since the gradation of the salvaged aggregate was within #12 surface specification limits and the virgin aggregate gradation was the specification mid point of #12 surface.

In other words four mixes were prepared; $(AC\text{-}20)_0$, $(AC\text{-}20)_1$, $(AC\text{-}20)_2$ and $(AC\text{-}20)_3$. All mixtures had the same aggregate type and gradation (#12 surface) and binders with consistency within AC-20 specification. The only difference is that the first is a completely virgin mix and the other three are recycled mixtures with AC-2.5, AE-150 and Mobilsol-30 as rejuvenating agents, respectively.

The control binder $(AC\text{-}20)_o$ was chosen to be virgin AC-20

(original binder present in RAP) typically used in Indiana to produce hot surface mixtures.

Three asphalt contents were used in mix preparations; 5.5%, 6% (original asphalt content present in RAP) and 6.5% by total weight of mixture.

The mixtures were compacted using the kneading compactor and evaluated using the pulse velocity, resilient modulus, indirect tensile strength, Hveem stability and Marshall stability tests. Compacted mixtures were also artificially aged and tested to study long term performance of recycled mixtures versus conventional virgin mixtures.

## 5.1. Pulse Velocity Test

The pulse velocity test equipment described previously in Chapter 3 was used. The transducers were connected to the transmitter and receiver nodes of the pulse generator. The pulse generator was allowed to send mechanical pulses through the transducer connected to the transmitter node. These pulses pass through the compacted specimen and are received by the transducer connected to the receiver. The time taken by this pulse is displayed on the timing unit screen, read and recorded. The test was conducted at room temperature, (72$^{o}$F). A sample holder was used to maintain contact between the transducers and the specimen. In addition a thin coating of starch gel was used to enhance

the contact between the sample and the transducers. For the pulse velocity computations the sample height was measured to the nearest 0.1 mm. Specimen weight and height were used to estimate the unit weight of the compacted mixtures.

The following parameters (response variables) were used to characterize the compacted mixtures;

(1) $$V = 32.81\frac{H}{t} \qquad (5.1)$$

where "H" is the specimen height in centimeters, "t" is the time displayed on screen (in micro seconds) and "V" is the pulse velocity in 1000 feet per second. The value "32.81" is the constant for units adjustment.

(2) $$E = v^2\frac{d}{C} \qquad (5.2)$$

where "E" is the instantaneous elastic modulus, "V" is the pulse velocity, "d" is the density and

$$C = \frac{1}{(3-6u)} + \frac{2}{(3+3u)} \qquad (5.3)$$

where "u" is the Poisson ratio. In order to estimate the instantaneous elastic modulus it was necessary to assume a value for u. The value theoretical ranges between zero and 0.5 and depends on the material property. Asphalt mixtures are believed to have a value in the range of 0.25 to 0.45. Schmidt (50) used a value of 0.35 at ambient temperature in the computations of the diametral resilient modulus. Mamlouk (52) indicated difficulties in laboratory determination of the Poisson ratio value, instead values of

0.3, 0.35 and 0.4 were assumed for "u" at 50, 75 and 100$^{o}$F respectively.

The estimation of "E" from pulse velocity test results of this study was based on assuming a Poisson ratio of 0.35 at test temperature of 72$^{o}$F. Using this assumption and adjusting the units, equation 5.2 can be expressed as follows:

$$E = V^2 \frac{d}{7442} \quad \text{at} 72^{o}F \tag{5.4}$$

where "E" is in psi, "V" is in feet per second and "d" is the unit weight in pound per cubic foot.

## 5.2. Resilient Modulus Test

The diametral resilient modulus equipment (Figure 2.1) described previously in Chapter 2 was used. The compacted test specimen was properly aligned as shown in Figure 2.1. The horizontal transducers were to be moved until they just contact the specimen. The load was applied across the vertical diameter of the specimen using two curved loading strips of 0.5 inch width and radius of 2 inch (same as specimen). The magnitude of the applied load was controlled by adjusting the pressure regulator for the compressed air to be 35 lb. and 50 lb. The load was applied every 3 seconds with a duration of 0.1 second. The horizontal deformation corresponding to each of the above two applied

loads were displayed on the recorder screen and recorded. The resilient modulus, MR, value corresponding to each load magnitude and resulting deformation was computed using the following equation:

$$MR = P\frac{(u+0.2734)}{hD} \qquad (5.5)$$

where "MR" is the resilient modulus in pound per square inch, psi, "h" is the specimen height in inches, "D" is the deformation in inches and "u" is the Poisson ratio. Poisson ratio was also assumed to be 0.35 at test temperature of $72^{o}$F.

## 5.3. Indirect Tensile Test

The indirect tensile test was conducted on Marshall testing apparatus. The specimen was loaded in a special frame which has two curved loading strips fixed to contact the specimen. Each strip is a 0.5 inch wide and 2 inches diameter to conform to the diameter of the specimen. Figure 2.4 shows a specimen being tested by this loading frame. The rate of loading was 2 inches per minute. Traces of load versus vertical deformation, till failure, were recorded by a strip graph recorder.

It is imperative to indicate that the theory of the test assumes isotropic and homogeneous material with a linear elastic behavior. It also assumes plane stresses in the specimen. These assumptions are not totally met in 4 inch

diameter and 2.5 inch height specimens and may not be exactly true for asphalt mixtures. However the random distribution of aggregate particles in the asphalt mixture tends to minimize the effect of hetorogeneity. In addition, this relatively fast rate of loading may tend to approximate a reasonable elastic behavior and minimize the effect of viscoelasticity.

Tia (83) and Mamlouk (52) introduced the following equations based on Hondros´s (87) analysis of stress strain relationship of the indirect tensile test. The equations are numerical solutions for Hondros integral equations.

$$d_v = \frac{P}{\pi HE}(11.257-0.193u) \tag{5.6}$$

$$d_h = \frac{P}{\pi HE}(0.841+3.141u) \tag{5.7}$$

$$\varepsilon_T = X_T \frac{0.1185u+0.03896}{0.2494u+0.0673} \tag{5.8}$$

where "$d_v$" is the vertical deformation in inches, "$d_h$" is the horizontal tensile deformation, "P" is the load in pounds, "H" is the specimen height in inches, "E" is the modulus of elasticity, "u" is the Poisson ratio, $X_T$ is the total horizontal deformation at failure in inches and "$\varepsilon_T$" is the total tensile strain at failure. The values of $d_v$, $d_h$, P, u and E are in the elastic range.

The following indirect tensile test parameters were used to characterize the conventional and recycled mixtures in the compacted state:

(1) Tensile strength = $S_T = 0.1556\frac{Pmax}{H}$ (5.9)

where $S_T$ is the tensile strength, psi, H is the specimen height in inches and $P_{max}$ is the load failure in pounds.

(2) Tensile Stiffness = $E_{IT} = \frac{Pl}{d_v H}3.56$ (5.10)

where "$E_{IT}$" is the tensile stiffness estimated using the initial tangent of load versus vertical deformation (Figure 5.1) in psi, H is the specimen height and $\frac{P}{d_v}$ is the slope of the initial tangent in pounds per inch. The value "3.56" were obtained by assuming a Poisson ratio of 0.35 in equation (5.6). Equation (5.10) is valid at any test temperature since a change of Poisson ratio from 0 to 0.5 will result in an error of $E_{IT}$ computation by just 1%.

(3) Tensile Strain = $\varepsilon_T = K \quad X_v$ (5.11)

where "$\varepsilon_T$" is total tensile horizontal strain at failure and "$X_V$" is the recorded vertical deformation at failure in inches. This formula was obtained from equation (5.8) by assuming Poisson ratio to be 0.27, 0.35 and 0.4 at test temperatures of 32, 72 and 104$^{o}$F and by replacing $X_T$ by $X_v$ using the deformation ratio that can be obtained by dividing equation (5.6) by (5.7). It is imperative to indicate that another assumption is introduced herein. The deformation ratio in the elastic range is assumed to be the same up to failure. The value of "K" was found to be 0.08, 0.09 and 0.09 at values of Poisson ratio of 0.27, 0.35 and 0.4 respectively, i.e.

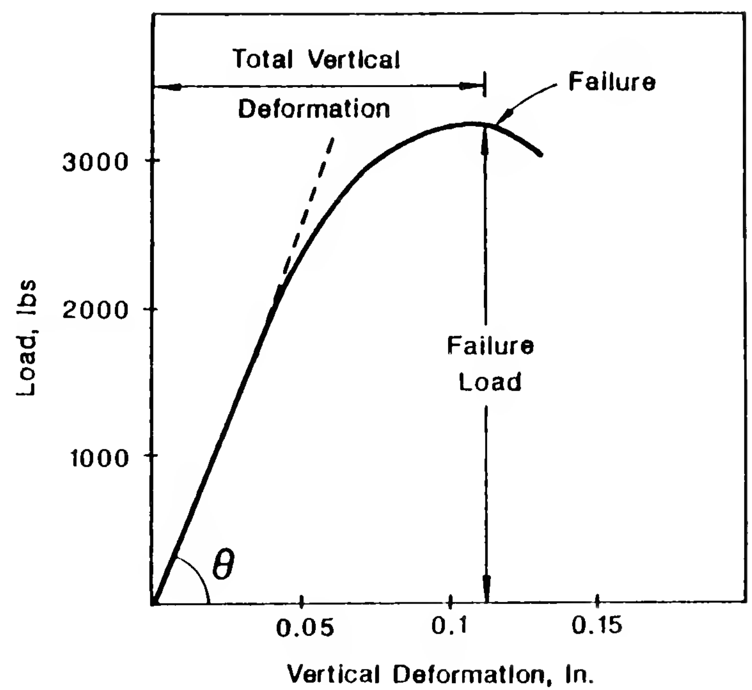



Figure 5.1 Typical Load-Vertical Deformation Trace During Indirect Tensile Test

$$\varepsilon_T = 0.08X_v \quad \text{at} 32^{o}F \tag{5.12}$$

$$\varepsilon_T = 0.09X_v \quad \text{at} 72^{o}F \tag{5.13}$$

$$\varepsilon_T = 0.09X_v \quad \text{at} 104^{o}F \tag{5.14}$$

These equations provide a reasonable estimate for the total horizontal tensile strain for comparative purposes. However, the exact values for $\varepsilon_T$ and u can be determined from traces of load versus vertical and horizontal deformations (52, 83). Mamlouk (52) and Tia (83) used the MTS electro-hydraulic machine for the determination of the Poisson ratio required for indirect tensile test parameters computations. However, Mamlouk used assumptions for Poisson ratio and Tia used the vertical deformation for the parameters computations.

(4) Modulus of Deformation = $E_d = \dfrac{S_T}{\varepsilon_T}$ (5.15)

where "$S_T$" is the indirect tensile strength, psi, "$\varepsilon_T$" is the total horizontal tensile strain and "$E_d$" is the modulus of deformation estimated from failure stress and failure strain in psi.

## 5.4. Hveem Stability Test

The Hveem stability test equipment (Figure 2.2) was used to determine the stability of the compacted mixtures. Standard test procedures, ASTM D 1560, were followed. The Hveem

stability value was computed using the following equation:

$$S = \frac{22.2}{(P_h D_2/(P_v - P_h) + 0.222}$$

where "S" is the Hveem stability value, dimensionless, "$P_v$" is the vertical pressure, 400 psi, "$P_h$" is the horizontal pressure in psi corresponding to a vertical pressure of 400 psi and "$D_2$" is the displacement of specimen.

## 5.5. Marshall Stability Test

The Marshall Stability test was conducted on $(AC-20)_0$, $(AC-20)_1$, $(AC-20)_2$ and $(AC-20)_3$ specimens with optimum binder content determined from pulse velocity, resilient modulus, indirect tensile strength and Hveem stability test results. The parameters used to characterize the different asphalt mixtures were; the Marshall stability in pounds, the Marshall flow in 0.01 inch and the Marshall stiffness defined as the stability divided by the flow in pounds per inch.

## 5.6. Test of Time-Temperature Effect on Compacted Mixtures

Pulse velocity, resilient modulus and indirect tensile strength test parameters were also used to characterize compacted specimens (virgin and recycled) after two weeks of storing in a forced draft oven at 140°F. In addition, the indirect tensile test parameters were also determined for non artificially aged compacted specimens at 32°F, 72°F and

$104^{\circ}F$. These response variables were obtained for $(AC\text{-}20)_0$, $(AC\text{-}20)_1$, $(AC\text{-}20)_2$ and $(AC\text{-}20)_3$ specimens containing optimum binder content.

## 5.7. Preparation of Specimens

Samples of the recycled asphalt pavement (RAP), virgin aggregate and virgin AC-20 were heated in an oven at $240^{\circ}F$ for one hour. The rejuvenators; AC-2.5, AE-150 and the Mobilsol-30 were heated in an oven at $180^{\circ}F$. The RAP, virgin aggregate and one of the rejuvenators were mechanically hot mixed for 2 minutes. Absolute virgin mixtures containing AC-20 and virgin aggregate were hot mixed similarly.

The loose samples containing 5.5%, 6%, and 6.5% asphalt binder for $(AC\text{-}20)_0$ and $(AC\text{-}20)_1$, $(AC\text{-}20)_2$ and $(AC\text{-}20)_3$ specimens were stored in an oven at $140^{\circ}F$ for 15 hours. Weight proportions for the various mixtures are presented in Appendix B.

The mixtures were then reheated to $240^{\circ}F$ and compacted using the standard California kneading compactor, ASTM D 1561, to form specimens of 4 inch diameter and approximately 2.5 inch height.

# CHAPTER 6

# CHARACTERISTICS OF COMPACTED HOT MIX RECYCLED ASPHALT PAVEMENT

## 6.1. Pulse Velocity Test

### 6.1.1. Pulse Velocity

Table 6.1 gives the pulse velocity values for the different compacted mixtures at different asphalt contents. The analysis of variance for these data (ANOVA) is presented in Table C.1 of Appendix C. The ANOVA results suggest that there were no significant differences between the pulse velocity values due to the change of asphalt content. However, the mean value at 6.5% was slightly lower than those values at 5.5% and 6.0%. Pulse velocity values of compacted recycled mixtures with AE-150 as a recycling agent, $(AC\text{-}20)_2$, were slightly lower than those values for absolute virgin mix, $(AC\text{-}20)_0$. Other recycled mixtures, $(AC\text{-}20)_1$ and $(AC\text{-}20)_3$, did not result in significant differences in the pulse velocity values compared to the $(AC\text{-}20)_0$ mix.

Table 6.1: Pulse Velocity Values in 1000 ft/second at 72°F for Compacted Mixtures at Different Asphalt Contents

| % A.C. | Mixture Types $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ | Mean |
|---|---|---|---|---|---|
| | 11.14 | 10.66 | 11.25 | 10.69 | |
| 5.5% | 11.55 | 11.24 | 10.49 | 10.65 | 10.99 |
| | 11.16 | 10.99 | 11.10 | 11.00 | |
| | 11.09 | 10.86 | 10.71 | 11.19 | |
| 6.0% | 11.27 | 11.23 | 10.63 | 11.28 | 11.04 |
| | 10.74 | 11.36 | 10.87 | 11.28 | |
| | 10.84 | 10.53 | 10.52 | 10.90 | |
| 6.5% | 11.21 | 10.79 | 10.98 | 10.51 | 10.80 |
| | 11.19 | 11.11 | 10.37 | 10.62 | |
| Mean | 11.13 | 10.97 | 10.77 | 10.90 | |

### 6.1.2. Density

Table 6.2 gives the density values for the different compacted specimens at asphalt contents of 5.5, 6.0 and 6.5%. Statistical analysis of variance indicated no significant difference between density values at the three asphalt contents. The density was determined by measuring the specimen weight and the average specimen height. The limited accuracy of this method in determining density could be a factor in the lack of variation in density with the change in asphalt content. In addition, the three asphalt contents (5.5, 6.0 and 6.5%) may be at or around the optimum content for maximum density and that may explain the resulting insignificant differences. The statistical analysis also indicated no significant difference between density values of the virgin and recycled mixtures. This could be attributed to the fact that all mixtures have the same aggregate gradation and binders with same consistency, which make them similar in compactibility and hence result in similar density.

### 6.1.3. Modulus of Elasticity

Table 6.3 presents the estimated modulus of elasticity values for the absolute virgin mixture, $(AC\text{-}20)_0$, and the recycled mixtures, $(AC\text{-}20)_1$, $(AC\text{-}20)_2$ and $(AC\text{-}20)_3$ at 5.5, 6.0 and 6.5% binder contents. The ANOVA suggests that the

Table 6.2: Density Values in gm/Cm$^3$ for Compacted Mixtures of Different Asphalt Contents

| % A.C. | Mixture Types $(AC-20)_o$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ | Mean |
|---|---|---|---|---|---|
| | 2.33 | 2.35 | 2.39 | 2.40 | |
| 5.5% | 2.39 | 2.37 | 2.39 | 2.41 | 2.38 |
| | 2.35 | 2.35 | 2.39 | 2.41 | |
| | 2.37 | 2.34 | 2.36 | 2.40 | |
| 6.0% | 2.36 | 2.37 | 2.39 | 2.40 | 2.37 |
| | 2.35 | 2.34 | 2.37 | 2.39 | |
| | 2.36 | 2.32 | 2.36 | 2.40 | |
| 6.5% | 2.37 | 2.38 | 2.38 | 2.40 | 2.37 |
| | 2.35 | 2.37 | 2.37 | 2.38 | |
| Mean | 2.36 | 2.36 | 2.38 | 2.40 | |

Table 6.3: Modulus of Elasticity Values in $10^6$ psi at 72°F for Compacted Mixtures at Different Asphalt Contents

| | Mixture Types | | | | |
|---|---|---|---|---|---|
| % A.C. | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ | Mean |
| | 2.421 | 2.234 | 2.531 | 2.302 | |
| 5.5% | 2.672 | 2.505 | 2.205 | 2.290 | 2.408 |
| | 2.452 | 2.375 | 2.469 | 2.439 | |
| | 2.447 | 2.316 | 2.274 | 2.515 | |
| 6.0% | 2.513 | 2.502 | 2.262 | 2.555 | 2.423 |
| | 2.268 | 2.532 | 2.346 | 2.546 | |
| | 2.326 | 2.159 | 2.191 | 2.387 | |
| 6.5% | 2.499 | 2.318 | 2.404 | 2.224 | 2.317 |
| | 2.462 | 2.454 | 2.133 | 2.250 | |
| Mean | 2.451 | 2.377 | 2.313 | 2.390 | |

modulus of elasticity estimation by pulse velocity is neither sensitive to the binder type nor to the change in asphalt content. No significant differences were detected at $\alpha = 0.05$. However, recycled mixtures especially those modified by AE-150 gave slightly lower modulus values than those of virgin mixtures. In addition, mixtures containing 6.5% binder content gave also slightly lower modulus values than those containing 5.5 and 6%. The ANOVA table is given in Appendix C, Table C.2.

## 6.2. Resilient Modulus Test

The diametral resilient modulus test was conducted on the same specimens tested by the non destructive pulse velocity test. Table 6.4 presents the modulus values corresponding to 5.5, 6.0 and 6.5% binder contents and the various mixture types. The test was sensitive to both binder content and the binder type present in the virgin and recycled mixtures, unlike the pulse velocity test, and significant differences were detected (Table C.3, Appendix C). Asphalt content of 5.5% displayed the maximum modulus values. The increase in asphalt content from 5.5% to 6.0% resulted in a significant decrease in the modulus value. Resilient modulus values at 6.5% asphalt content were also slightly lower than those values at 6.0% but significantly lower than the modulus values at 5.5%.

Table 6.4: Diametral Resilient Modulus Values in $10^6$ psi at 72°F for Compacted Mixtures at Different Asphalt Contents

| | Mixture Types | | | | |
|---|---|---|---|---|---|
| % A.C. | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ | Mean |
| | 0.755 | 0.653 | 0.675 | 0.671 | |
| 5.5% | 0.936 | 0.648 | 0.706 | 0.697 | 0.717 |
| | 0.717 | 0.659 | 0.736 | 0.752 | |
| | 0.690 | 0.440 | 0.466 | 0.610 | |
| 6.0% | 0.689 | 0.510 | 0.404 | 0.645 | 0.590 |
| | 0.738 | 0.596 | 0.556 | 0.739 | |
| | 0.726 | 0.434 | 0.353 | 0.635 | |
| 6.5% | 0.615 | 0.594 | 0.462 | 0.466 | 0.543 |
| | 0.642 | 0.593 | 0.336 | 0.658 | |
| Mean | 0.723 | 0.570 | 0.522 | 0.653 | |

Notes:

*Least significant difference between means, mixture type = 0.07 * $10^6$ psi

*Least significant difference between means, %AC = 0.06 * $10^6$ psi

* $\alpha$= 0.05

Virgin mixture, $(AC\text{-}20)_0$, displayed the largest modulus values compared to recycled mixtures, as can be observed from Table 6.4. Virgin mixtures, $(AC\text{-}20)_0$, gave the highest modulus values followed by recycled mixture with Mobilsol-30 as a rejuvenator, $(AC\text{-}20)_3$ and the recycled mixtures containing AC-2.5 and AE-150, $(AC\text{-}20)_1$ and $(AC\text{-}20)_2$, as modifiers respectively. $(AC\text{-}20)_2$ mixtures gave the lowest modulus values. The trend is identical to that obtained for pulse velocity and modulus of elasticity estimated from pulse velocity test. However, the statistical significance were detected herein while it was not detected from pulse velocity test results.

## 6.3. Indirect Tensile Test

Specimens tested by the pulse velocity and the resilient modulus test equipment were loaded to failure by the indirect tensile loading mechanism conducted using the Marshall loading frame. Four parameters were obtained from the test results; (1) the indirect tensile strength, (2) the indirect tensile stiffness, (3) the failure tensile strain and (4) the modulus of deformation. These parameters were obtained for the four mixtures; $(AC\text{-}20)_0$, $(AC\text{-}20)_1$, $(AC\text{-}20)_2$ and $(AC\text{-}20)_3$ at three asphalt contents 5.5%, 6% and 6.5% by total weight of mix. The output results are introduced in Tables 6.5 through 6.8 and the statistical ANOVA are presented in Tables C.4 through C.7 of Appendix C.

Table 6.5: Indirect Tensile Strength Values in psi at 72°F for Compacted Mixtures at Different Asphalt Contents

| | Mixture Types | | | | |
|---|---|---|---|---|---|
| % A.C. | $(AC\text{-}20)_0$ | $(AC\text{-}20)_1$ | $(AC\text{-}20)_2$ | $(AC\text{-}20)_3$ | Mean |
| | 185 | 158 | 152 | 159 | |
| 5.5% | 193 | 154 | 148 | 152 | 165 |
| | 182 | 161 | 155 | 181 | |
| | 178 | 128 | 130 | 143 | |
| 6.0% | 176 | 124 | 116 | 157 | 150 |
| | 177 | 146 | 153 | 166 | |
| | 166 | 112 | 112 | 145 | |
| 6.5% | 158 | 138 | 130 | 122 | 140 |
| | 162 | 142 | 134 | 157 | |
| Mean | 175 | 140 | 137 | 154 | |

Notes:

*L.S.D. between means, mix type = 11.0 psi

*L.S.D. between means, %AC = 9.0 psi

* $\alpha = 0.05$

Table 6.6: Indirect Tensile Stiffness Values in $10^4$ psi at $72^{o}F$ for Compacted Mixtures at Different Asphalt Contents.

| | Mixture Types | | | | |
|---|---|---|---|---|---|
| % A.C. | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ | Mean |
| | 8.00 | 6.91 | 7.01 | 8.02 | |
| 5.5% | 7.65 | 7.33 | 6.16 | 7.81 | 7.36 |
| | 8.35 | 7.76 | 6.70 | 7.60 | |
| | 6.95 | 5.97 | 5.88 | 7.01 | |
| 6.0% | 7.31 | 6.33 | 6.24 | 7.73 | 6.81 |
| | 7.67 | 6.69 | 6.60 | 7.37 | |
| | 6.31 | 6.03 | 6.08 | 6.18 | |
| 6.5% | 6.29 | 6.00 | 5.92 | 6.26 | 6.15 |
| | 6.27 | 6.06 | 6.00 | 6.34 | |
| Mean | 7.20 | 6.56 | 6.29 | 7.15 | |

Notes:

*L.S.D. between means, mix type = 0.29 * $10^4$ psi

*L.S.D. between means, %AC = 0.25 * $10^4$ psi

* $\alpha = 0.05$

Table 6.7: Failure Tensile Strain Values in 1/1000 inch/inch at 72°F for Compacted Mixtures at Different Asphalt Contents

| | Mixture Types | | | | |
|---|---|---|---|---|---|
| % A.C. | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ | Mean |
| | 9.04 | 7.14 | 7.68 | 6.33 | |
| 5.5% | 7.86 | 7.50 | 7.68 | 6.33 | 7.37 |
| | 7.23 | 6.78 | 8.14 | 6.78 | |
| | 9.94 | 9.94 | 9.49 | 7.23 | |
| 6.0% | 9.04 | 8.59 | 10.30 | 7.68 | 8.54 |
| | 8.14 | 7.68 | 8.14 | 6.33 | |
| | 9.94 | 10.85 | 10.62 | 7.68 | |
| 6.5% | 9.49 | 8.59 | 9.49 | 10.12 | 9.60 |
| | 9.04 | 8.59 | 11.75 | 9.04 | |
| Mean | 8.86 | 8.41 | 9.25 | 7.50 | |

Notes:

*L.S.D. between means, mix type = $0.82 * 10^{-3}$ inch/inch

*L.S.D. between means, % AC = $0.71 * 10^{-3}$ inch/inch

* $\alpha = 0.05$

Table 6.8: Tensile Modulus of Deformation in $10^3$ psi at $72^oF$ for Compacted Mixtures at Different Asphalt Contents

| | Mixture Types | | | | |
|---|---|---|---|---|---|
| % A.C. | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ | Mean |
| | 20.5 | 22.1 | 19.8 | 25.1 | |
| 5.5% | 24.6 | 20.5 | 19.3 | 24.0 | 22.5 |
| | 25.2 | 23.7 | 19.0 | 26.7 | |
| | 17.9 | 12.9 | 13.7 | 19.8 | |
| 6.0% | 19.5 | 14.4 | 11.3 | 20.4 | 18.0 |
| | 21.7 | 19.0 | 18.8 | 26.2 | |
| | 16.7 | 10.3 | 10.6 | 18.9 | |
| 6.5% | 16.7 | 16.1 | 13.7 | 12.1 | 14.9 |
| | 17.9 | 16.5 | 11.4 | 17.4 | |
| Mean | 20.1 | 17.3 | 15.3 | 21.2 | |

Notes:

*L.S.D. between means, mix type = 2.4 * $10^3$ psi

*L.S.D. between means, % AC = 2.1 * $10^3$ psi

### 6.3.1. Indirect Tensile Strength

The indirect tensile strength values followed the same trend as the diametral resilient modulus values. Higher tensile strength values were obtained at 5.5% asphalt content. An increase in the asphalt content by 0.5% resulted in a decrease in the strength by 10-15 psi (Table 6.5). Virgin mixtures gave also higher strength values than recycled mixture. Lowest strength values were obtained from $(AC-20)_2$ mixtures with recycled binder modified by AE-150.

### 6.3.2. Indirect Tensile Stiffness

The traces of the load-vertical deformation obtained during the indirect tensile test were used in the computation of the indirect tensile stiffness as well as the indirect tensile strength. The stiffness was estimated using the initial tangent slope of the load-deformation plot. Statistical analysis indicated a significant decrease in the stiffness by the increase in asphalt content from 5.5% to 6.5%. Mixtures $(AC-20)_0$ and $(AC-20)_3$ almost have the same stiffness and mixtures $(AC-20)_1$ and $(AC-20)_2$ also have similar stiffness. However, mixtures $(AC-20)_1$ and $(AC-20)_2$ stiffness values were significantly lower than those values for $(AC-20)_0$ and $(AC-20)_3$ mixtures.

### 6.3.3. Failure Tensile Strain

The vertical deformation at failure obtained from the

indirect tensile test was used to estimate the failure tensile strain. Paving mixtures with low tensile strain values have a tendency to develop low temperature cracking problems in the field, while those with high strain values may cause rutting problems. Recycled mixtures are believed to have low tensile strain values due to the presence of hardened old asphalt in the mix. However, this is only a one side analysis, since the recycled mixtures also contain soft asphalt material (rejuvenator). Table 6.7 presents the failure tensile strain values for the $(AC-20)_0$, $(AC-20)_1$, $(AC-20)_2$, and $(AC-20)_3$ mixtures at asphalt contents of 5.5, 6.0 and 6.5%. Statistical analysis indicated that the increase in asphalt content was correlated to a significant increase in the failure tensile strain values. Considering the $(AC-20)_0$ virgin mixture as the basis of comparison, $(AC-20)_1$ mixtures showed slightly lower failure strain values while $(AC-20)_2$ mixture showed slightly higher failure strain values. Mixture $(AC-20)_3$ with Mobilsol-30 as a rejuvenator and with the highest percentage of RAP material gave significantly low failure strain values compared to the virgin $(AC-20)_0$ mixture.

### 6.3.4. Tensile Modulus of Deformation

The tensile modulus of deformation defined as the ratio of the indirect tensile strength to the tensile failure strain

was estimated for the 12 treatment combinations (Table 6.8). Highest modulus values were obtained at asphalt content of 5.5% with a significant reduction when the asphalt content increases to 6.0% and from 6.0% to 6.5%. $(AC-20)_3$ and $(AC-20)_0$ mixtures also gave the highest modulus values while mixture $(AC-20)_2$ gave the lowest.

## 6.4. Hveem Stability Test

The standard Hveem stability test, ASTM D 1560, was conducted on specimens compacted by the standard kneading compactor (ASTM D 1561). After the Hveem stability test, each specimen was removed from the stabilometer, placed in an oven for one hour at $140^{o}F$ and loaded to failure by the Marshall testing apparatus. The stability values obtained from the Marshall testing equipment were called the pseudo-Marshall stability values. The Hveem stability test is known to create some distress in specimen during the test even though it is confined in the stabilometer during loading. It is imperative to indicate that these pseudo-Marshall stability values are not representative of the actual Marshall stability values.

Tables 6.9 and 6.10 present the Hveem and pseudo-Marshall stability values for the virgin and recycled mixtures at different asphalt contents. The Hveem stability test was very sensitive to asphalt content and indicated that the

Table 6.9: Hveem Stability Values at 140$^{o}$F for the Different Compacted Mixtures

| % A.C. | $(AC\text{-}20)_0$ | $(AC\text{-}20)_1$ | $(AC\text{-}20)_2$ | $(AC\text{-}20)_3$ | Mean |
|---|---|---|---|---|---|
| | Mixture Types | | | | |
| | 48 | 49 | 48 | 49 | |
| 5.5% | 52 | 48 | 49 | 48 | 48.8 |
| | 50 | 48 | 47 | 49 | |
| | 45 | 45 | 44 | 43 | |
| 6.0% | 45 | 43 | 42 | 44 | 43.9 |
| | 44 | 44 | 43 | 45 | |
| | 37 | 37 | 36 | 37 | |
| 6.5% | 36 | 36 | 34 | 36 | 35.7 |
| | 34 | 35 | 35 | 35 | |
| Mean | 43.4 | 42.8 | 42.0 | 42.9 | |

Notes:

*Least significant difference, % AC = 0.9 (Appendix C)

Table 6.10: Pseudo Marshall Stability Values in Pounds at 140°F for the Different Compacted Mixtures

| % A.C. | $(AC\text{-}20)_0$ | $(AC\text{-}20)_1$ | $(AC\text{-}20)_2$ | $(AC\text{-}20)_3$ | Mean |
|---|---|---|---|---|---|
| | Mixture Types | | | | |
| | 2450 | 2050 | 1850 | 2150 | |
| 5.5% | 2500 | 2150 | 1900 | 2350 | 2138 |
| | 2550 | 1950 | 1750 | 2000 | |
| | 2250 | 1850 | 1700 | 1900 | |
| 6.0% | 2200 | 1750 | 1600 | 1800 | 1929 |
| | 2300 | 1950 | 1750 | 2100 | |
| | 2000 | 1650 | 1500 | 1900 | |
| 6.5% | 1950 | 1750 | 1550 | 1700 | 1721 |
| | 2050 | 1600 | 1400 | 1600 | |
| Mean | 2250 | 1856 | 1667 | 1944 | |

Notes:

*L.S.D., Mix type = 91 pounds, (Appendix C)

*L.S.D., % AC = 79 pounds, (Appendix C)

*The above values are not representative of the actual Marshall Stability values.

maximum stability was obtained at 5.5%. However, the test failed to discriminate among the various mixtures. No significant difference was obtained between the virgin mixture $(AC-20)_0$ and the recycled mixtures, as suggested by the ANOVA results (Table C.8).

On the other hand, the pseudo-Marshall stability values were sensitive to binder type present in the various mixtures as well as the asphalt content and significant differences were detected by the ANOVA results (Table C.9).

Virgin mixtures, $(AC-20)_0$, gave the highest pseudo-Marshall stability values followed by RAP modified by Mobilsol-30, RAP modified by AC-2.5 and RAP modified by AE-150 respectively.

## 6.5. Marshall Stability Values

Asphalt content of 5.5% by weight of mix gave the maximum resilient modulus, indirect tensile strength, indirect tensile stiffness, tensile modulus of deformation, pseudo-Marshall stability and Hveem stability. Virgin and recycled mixtures with a binder content of 5.5% were prepared as previously described in Chapter 5, but were compacted, as required for Marshall Stability Test, by mechanically applying 75 blows per specimen face. Table 6.11 gives the Marshall stability test parameters for both virgin and recycled mixtures. High stability values were obtained for

Table 6.11: Marshall Stability Test Values at 140°F for the Compacted Mixtures at 5.5% Asphalt Content

| Mixtures | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| | 2600 | 2150 | 2050 | 2250 |
| Stability | 2200 | 2200 | 1900 | 2200 |
| in Pounds | 2250 | 2300 | 2100 | 2350 |
| | 12 | 11.0 | 13.0 | 12.0 |
| Flow, | 11.5 | 11.5 | 11.0 | 11.0 |
| 0.01 inch | 11.0 | 12.0 | 14.0 | 13.0 |
| Marshall | 21,667 | 19,546 | 15,769 | 18,750 |
| Stiffness | 19,130 | 19,130 | 17,273 | 20,000 |
| lb./inch | 20,445 | 19,167 | 15,000 | 18,077 |
| Marshall | 30,797 | 29,651 | 27,028 | 30,797 |
| Index | 30,216 | 28,563 | 26,541 | 29,651 |
| lb./inch | 29,651 | 29,100 | 27,527 | 26,541 |

Notes:

*Marshall stiffness is the ratio between the stability and flow.

*Marshall index is the slope of the initial tangent of stability-flow plot.

all mixtures. However $(AC-20)_0$ virgin mixtures gave the highest values while $(AC-20)_2$ mixtures gave the lowest stability values. Unit weight values of the different specimens are introduced in Table C.10, Appendix C.

## 6.6. Relationship Between Various Test Results

The relationships between response variables of the various tests conducted in this part of the study to characterize recycled mixtures were investigated. Resilient modulus and indirect tensile strength test results were strongly correlated. Both tests were sensitive to binder content and binder type (virgin or recycled) present in the compacted specimens. The Hveem stability test was sensitive to binder content but failed to discriminate between different binder types and hence was poorly correlated to resilient modulus and indirect tensile test response variables. Pulse velocity test failed completely to identify different mixtures and was not even sensitive to changes in binder content and hence was very poorly correlated to other test results.

### 6.6.1. Resilient Modulus Versus Indirect Tensile Test Parameters

Regression equations and correlations between the resilient modulus (dependent variable) and the indirect tensile test results (independent variable) were investigated. The

resilient modulus values and the corresponding indirect tensile strength values are plotted in Figure 6.1. A correlation coefficient of 0.885 was obtained between the two variables. A linear regression equation was fitted, using all the 36 data points, with an $R^2$ value of 0.782. This equation is shown below:

$$MR = 5.42\ S_T - 204$$

where MR = Resilient Modulus, $10^3$ psi.

$S_T$ = Indirect tensile strength, psi.

Meanwhile, the correlation coefficient between the resilient modulus and the corresponding indirect tensile stiffness was 0.925. The relationship between the two parameters is shown in Figure 6.2. A linear regression equation with an $R^2$ of 0.856 was fitted between them for the 12 treatment combinations data points. Each data point is the average of 3 replicates at each treatment combination. This regression equation is shown below:

$$MR = 13.34\ E_{IT} - 29\ 0$$

where MR = Resilient Modulus, $10^3$ psi.

$E_{IT}$ = Indirect tensile stiffness, $10^3$ psi.

In addition, the correlation coefficient between resilient modulus and modulus of deformation, $E_d$, estimated from indirect tensile test was 0.872. A linear regression equation with an $R^2$ value of 0.760 was fitted between them

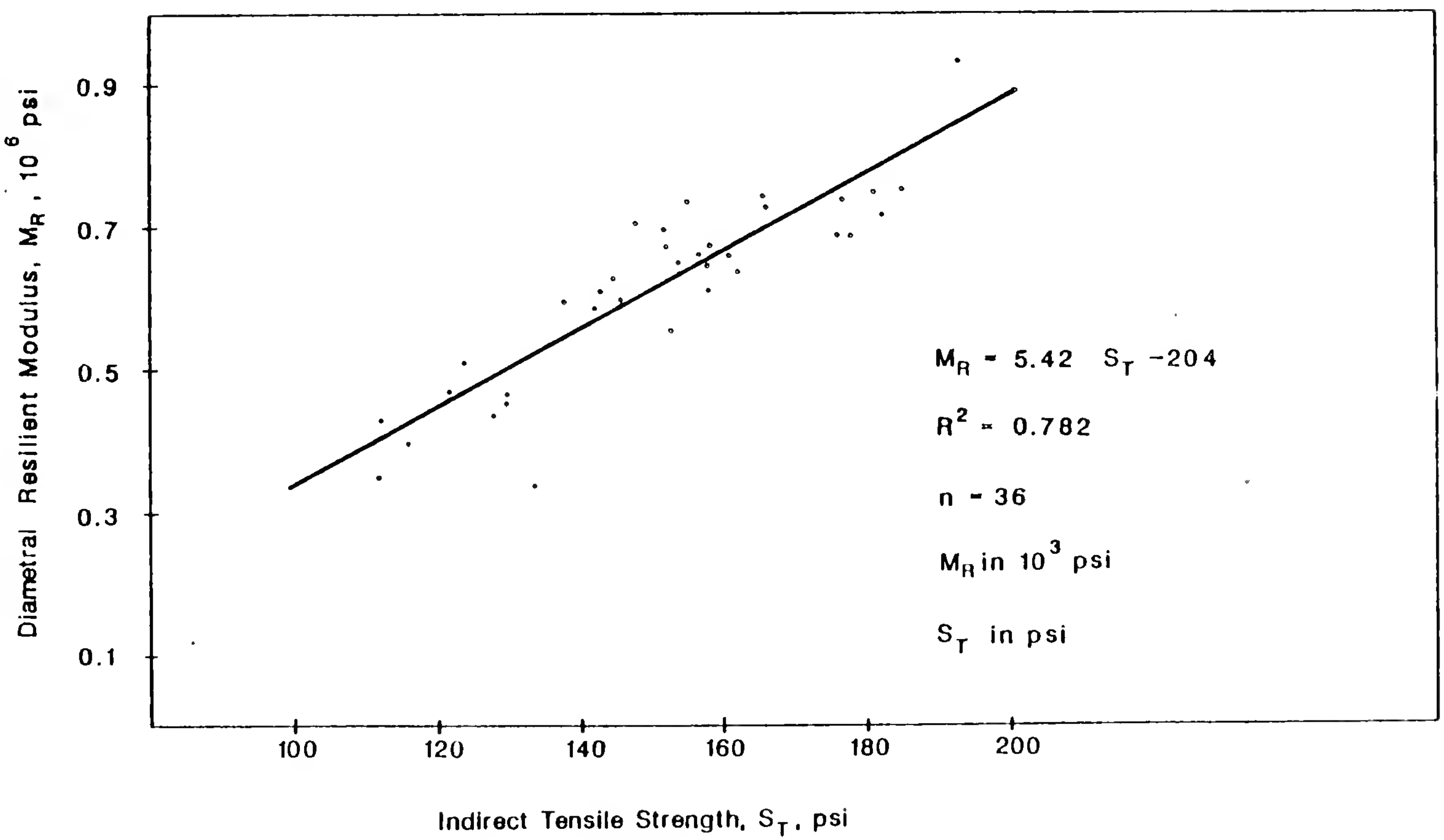



Figure 6.1 Relationship Between Diametral Resilient Modulus and Indirect Tensile Strength

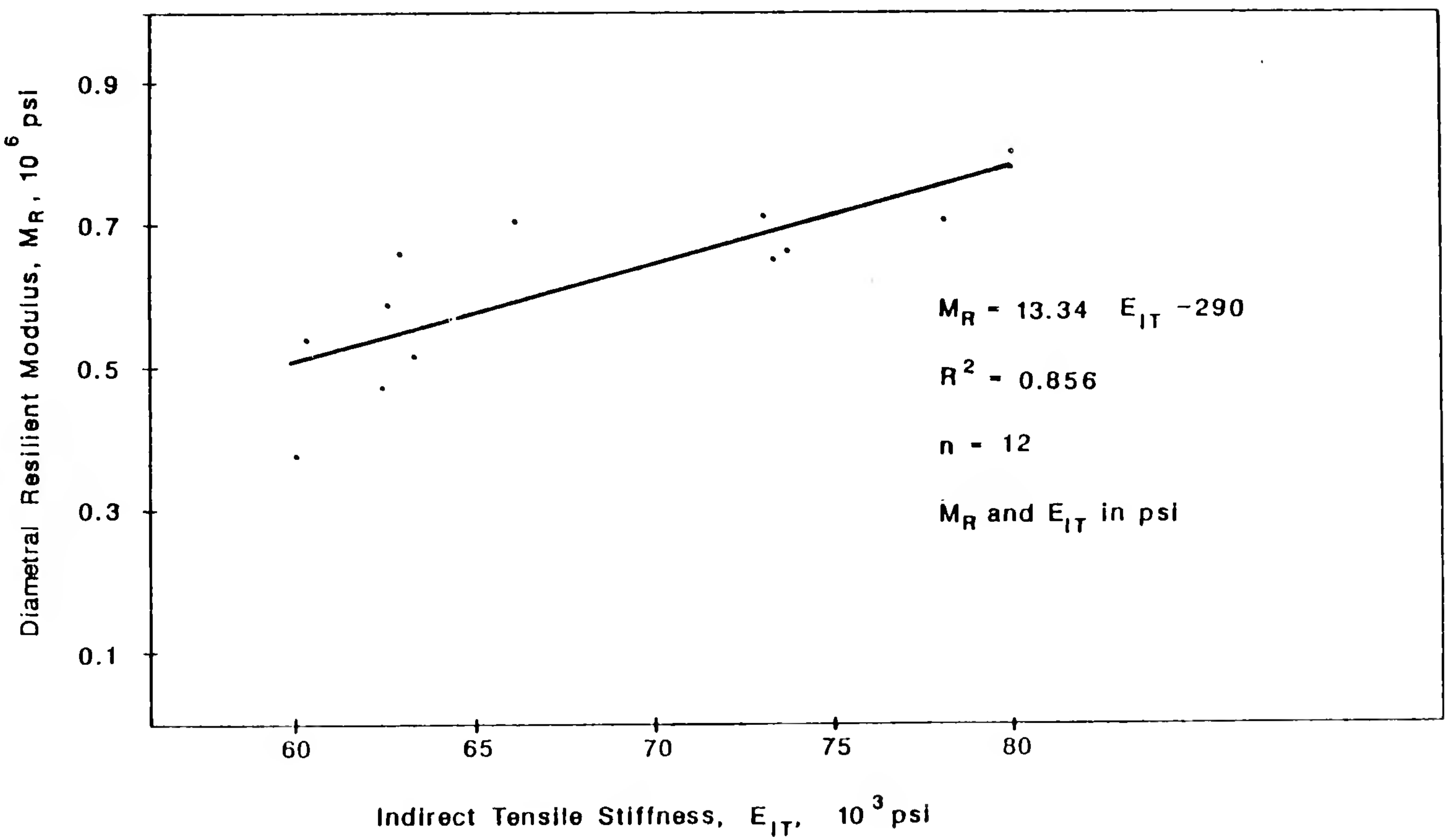



Figure 6.2 Relationship Between Diametral Resilient Modulus and Indirect Tensile Stiffness

(Figure 6.3). Data points used were the average of each 12 treatment combinations. This equation is given below:

$$MR = 0.025\ E_d + 0.158$$

where MR = diametral resilient modulus, $10^6$ psi.

$E_d$ = Modulus of deformation, $10^3$ psi.

It is obvious that there is a good correlation between the diametral resilient modulus values and the indirect tensile test results. Since the indirect tensile test is easier to perform, the previous equations can be used to predict the $M_R$ value from the indirect tensile strength, stiffness or modulus of deformation values. However these equations are statistically valid only within or close to the range of values obtained in this study.

### 6.6.2. Empirical Values

Presented herein are some empirical values that can give a general idea about the characteristics of asphalt paving mixtures. The usual judgment of a highway engineer, for two asphaltic mixtures to be used in pavement construction and having Marshall stabilities of 700 and 2000 pounds and Hveem stabilities of 20 and 40, is that the first is generally a poor mixture and the second is generally a good mixture. However, the familiarity with other mechanical property values is not the same as for the better known Marshall and Hveem stability values. The following empirical values are

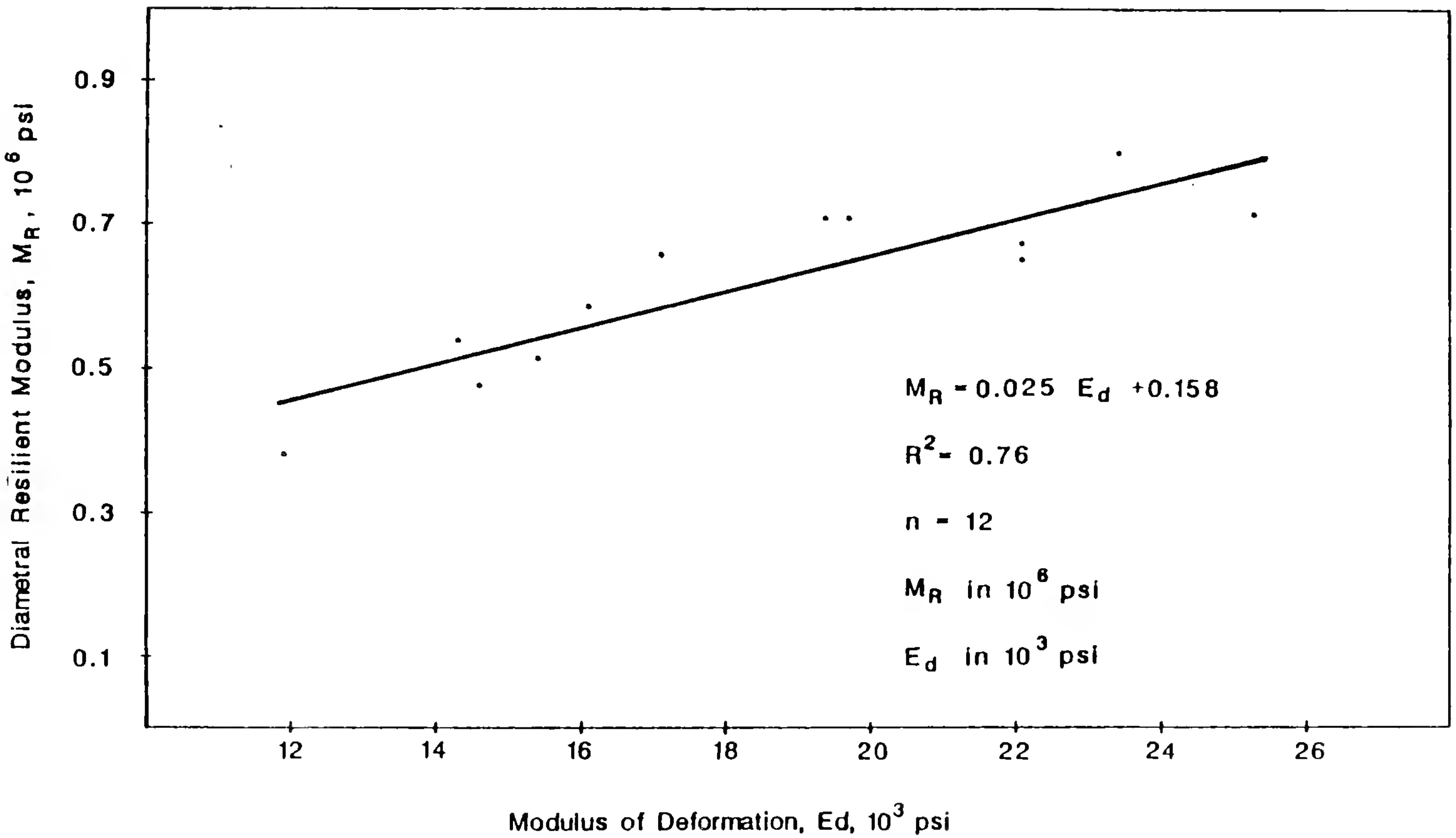



Figure 6.3 Relationship Between Diametral Resilient Modulus and Modulus of Deformation

the overall means of the various response variables obtained in this part of the study and can give a rough idea about other mechanical property values.

Asphalt mixtures with a Hveem stability value in the range of 34-52 and 43 average value, and a Marshall stability value in the range of 1400-2550 pounds and 1930 pounds average value, roughly have the following empirical values at ambient temperature ($72^{o}$F):

1. Pulse velocity, through compacted specimens, in the range of 10,500-11,500 feet per second with an average value of 11000 feet per second. This value for structural concrete is roughly 15000 feet per second.

2. Modulus of Elasticity in the range of $2.1-2.7 \times 10^{6}$ psi with an average of $2.4 \times 10^{6}$ psi.

3. Resilient modulus in the range of 340-940 ksi with an average of 620 ksi.

4. Tensile strength in the range of 110-190 psi with an average of 150 psi. Typical tensile strength of structural concrete is 400 psi.

5. Tensile strain at failure in the range of 0.006-0.012 with an average of 0.009. Typical failure tensile strain of structural concrete is 0.001.

6. Tensile stiffness, $E_{IT}$, in the range of 60,000-80,000 psi with an average of 68,000 psi.

7. Tensile modulus of deformation, $E_d$, in the range of 10,000-27,000 psi with an average of 18,000 psi.

## 6.7. Summary of Results

Three hot recycled bituminous mixtures in the compacted state were characterized using the pulse velocity, resilient modulus and indirect tensile tests beside the conventional methods (Marshall and Hveem). The recycled mixtures contained binders with the same consistency as of AC-20 and aggregate gradation of #12 surface. The three recycling agents used in the mixtures were AC-2.5, AE-150 and Mobilsol-30. Every recycled mixture contained old asphalt, salvage aggregate, virgin aggregate and only one of these recycling agents. A virgin mixture containing virgin aggregate and virgin AC-20 were characterized by the same tests for comparative purposes. Binder contents in the mixtures were 5.5, 6.0 and 6.5% by total weight of the mix.

The main findings can be summarized as follows:

1. Virgin mixture stiffness, resilient modulus and strength values were in general higher than those of recycled mixtures.

2. The recycled mixtures, with AE-150 as a rejuvenator, demonstrated lower stiffness and strength values than when compared to the other 3 mixtures. Considering this observation and the one obtained in characterizing the recycled binder separately by the thin film oven test (Chapter 4), the AE-150 may be a poor choice as a rejuvenator for hot mix recycling.

3. Asphalt content of 5.5% yielded the highest stiffness and strength values for all mixtures.

4. Hveem stability test was sensitive to binder content but did not discriminate between the mixtures (virgin or recycled). Hveem stability values for all mixtures at 5.5% binder content were reasonably higher than minimum limit specified for heavy traffic category which is 37.

5. Pulse velocity test parameters were also neither sensitive to binder content nor to the binder type present in the mixtures. This could be attributed to the similarity between all mixtures in the elastic range caused by the very high rate of application of pulses.

6. Resilient modulus test was very sensitive to both binder content and binder type present in the mixtures.

7. The indirect tensile test appeared to be best for the characterization of hot mix recycled asphalt pavements. The test was sensitive to binder content and binder type. It gives four responses for each compacted specimen; tensile strength, tensile strain, stiffness and modulus of deformation. Each of these parameters can be used in the material characterization. Similarity in loading conditions and distribution of stresses between the resilient modulus and the indirect tensile tests make both test parameters strongly correlated.

8. Marshall stability values for all mixtures at 5.5% binder content were significantly higher than the minimum value specified by the Asphalt Institute for heavy traffic category which is 750 lb.

# CHAPTER 7

# LONG TERM BEHAVIOR OF COMPACTED HOT MIX RECYCLED ASPHALT PAVEMENT

## 7.1. Introduction

Asphalt paving mixtures have two completely different long term behaviors when they are used in pavement. The first is the viscoelastic behavior in which they are similar to any other construction material which undergo a reduction in the stiffness and strength properties under loading for a long period of time. This behavior is also accompanied by an increase in the deformation with time even under constant amount of tolerable static loading or the so called creep properties. Large permanent deformation levels even without breakdown are not tolerable in pavement since it is considered a functional failure type.

The second is the age hardening behavior in which the asphalt paving material will develop an increase in the stiffness properties with time caused by the hardening of the asphalt binder under weathering, oxidation and the other environmental actions. This gain, however, may be detrimental for the pavement if it occurred at a high rate. The increase in stiffness would cause the pavement to be more brittle and cracks would occur at low deformation levels.

These two long term behaviors were investigated herein for recycled mixtures and compared with a virgin mixture.

## 7.2. Viscoelastic Behavior

The viscoelastic behavior of $(AC-20)_0$, $(AC-20)_1$, $(AC-20)_2$ and $(AC-20)_3$ mixtures was investigated using two approaches.

The first approach was to evaluate the effect of different qualitative loading rates on the resulting stiffness of the compacted specimens and the second was to study the effect of different testing temperatures on the tensile strength and stiffness characteristics of the virgin and recycled mixtures. In other words, the time dependent viscoelastic behavior was simulated by loading rate and temperature dependent behaviors.

### 7.2.1. Effect of Loading Rate

No special test were added for the study of the effect of loading rate on the stiffness properties of the compacted mixtures. Stiffness characteristics at various loading rates and $72^{o}F$ were previously determined in Chapter 6. The modulus of elasticity estimated by pulse velocity test resembles the stiffness at the fastest loading rate, resilient modulus represents the stiffness at slower loading rate and indirect tensile stiffness represents the stiffness at the slowest loading rate.

Figure 7.1 presents a histogram of the quantitative change in stiffness estimation with the qualitative change in loading rate used for these estimations. The illustration suggests that the short term elastic behavior of the virgin and recycled mixtures is identical as can be seen from modulus of elasticity values. However, with the qualitative reduction in loading rate from the one of pulse velocity to the one of the resilient modulus, a reduction in estimated stiffness is observed. In addition, differences are detected between virgin and recycled mixtures. Time dependent behavior, temperature dependent behavior and loading rate behavior are equivalent in the sense that: Material response after a short period of loading, at low temperature or at a high rate of loading is elastic. Material response after a long period of loading, at high temperature or at a low rate of loading is viscous. Material stiffness, strength or modulus values are larger after short periods of loading, low temperature or high rate of loading than those values after long periods of loading, high temperature or low rate of loading.

The qualitative change in stiffness with the qualitative change in loading rate can be explained as follows:

1. Virgin and recycled mixtures may have the same stiffness at the time of construction; time step 1. This stiffness is 100 considering a rank of 1-100.

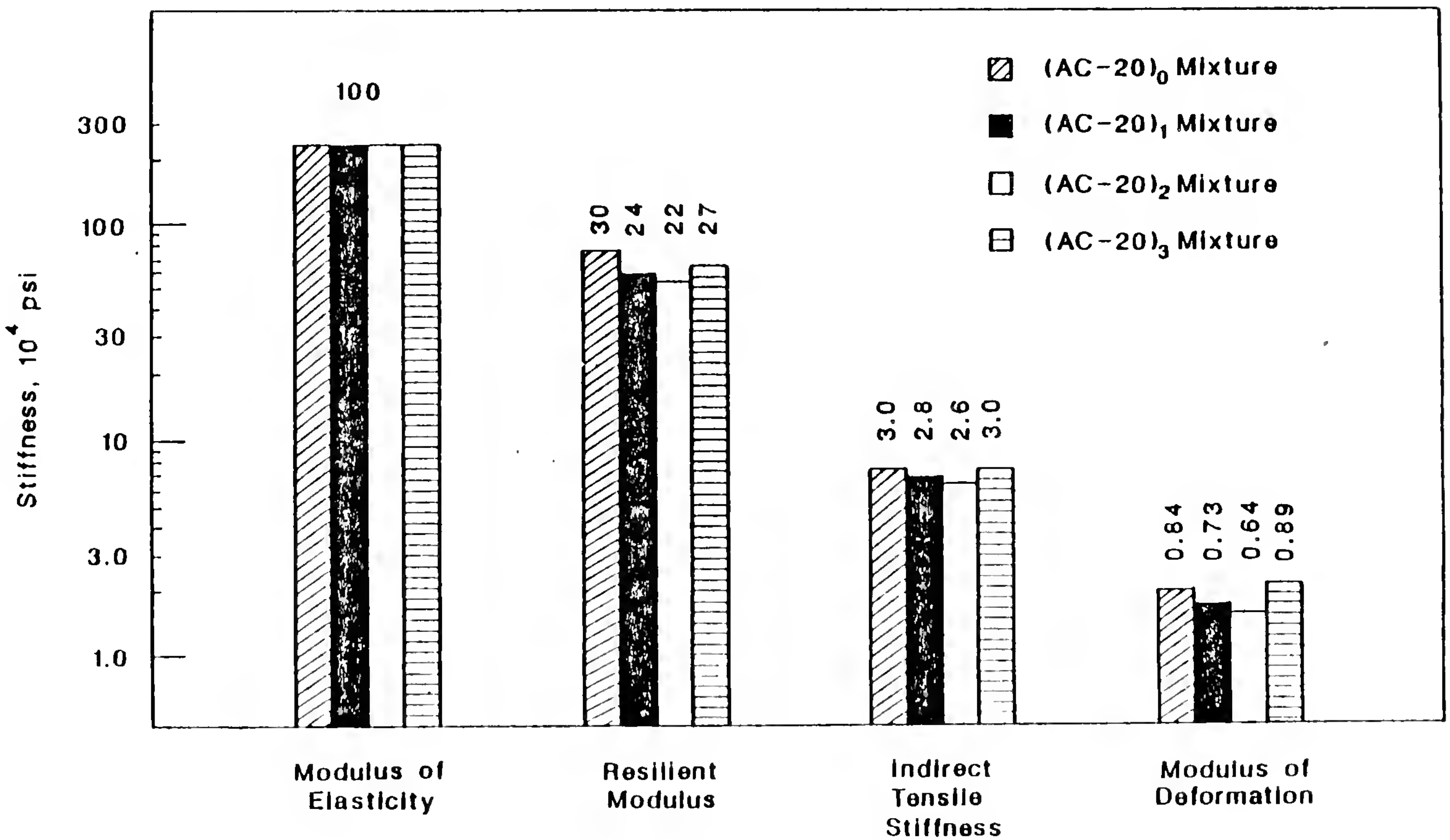



Figure 7.1 Drop in Stiffness Value Due to The Reduction in Loading Rate

2. After a period of time the stiffness of the conventional virgin mixture decreased from 100 to 30 while for recycled mixtures with AC-2.5, AE-150 and Mobilsol-30 as rejuvenators the stiffness decreased to 24, 22 and 27 respectively, time step 2.

3. After another period of time the virgin mixture stiffness diminished to 3.0 and the other three recycled mixtures stiffness values were reduced to 2.8, 2.6 and 3.0 respectively, time step 3.

It can be seen that the virgin mix has slightly the best long term viscoelastic performance followed by the recycled mix modified by Mobilsol-30, the one modified by AC-2.5 and the recycled mix with AE-150 as a rejuvenator respectively. However, the analysis herein is on comparative and qualitative basis with no specification limit to disapprove any of the recycled mixtures.

### 7.2.2. Temperature Dependent Behavior

The indirect tensile test was conducted on virgin and recycled mixtures having 5.5% binder content by mix total weight at 32, 72 and 104$^{o}$F.

Tables 7.1 through 7.4 presents the indirect tensile test parameters; strength, stiffness, modulus of deformation and tensile strain values at the above three temperatures. In

Table 7.1: Indirect Tensile Strength Values in psi for Compacted Specimens at Various Testing Temperatures

| Testing Temperature | Mix Type $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| | 554 | 542 | 464 | 499 |
| $32^oF$ | 546 | 518 | 486 | 534 |
| | 580 | 530 | 475 | 568 |
| | 185 | 158 | 152 | 159 |
| $72^oF$ | 193 | 154 | 148 | 152 |
| | 182 | 161 | 155 | 181 |
| | 65 | 55 | 56 | 54 |
| $104^oF$ | 61 | 57 | 53 | 64 |
| | 63 | 58 | 54 | 59 |

Note:

*Asphalt Content is 5.5% by total weight of mix.

Table 7.2: Indirect Tensile Stiffness Values in $10^4$ psi for Compacted Specimens at Various Testing Temperatures

| Testing Temperature | Mix Type $(AC\text{-}20)_0$ | $(AC\text{-}20)_1$ | $(AC\text{-}20)_2$ | $(AC\text{-}20)_3$ |
|---|---|---|---|---|
| | 26.29 | 27.97 | 25.52 | 22.81 |
| $32^oF$ | 29.62 | 26.44 | 23.43 | 26.07 |
| | 27.96 | 24.91 | 24.49 | 30.00 |
| | 8.00 | 6.91 | 7.01 | 8.02 |
| $72^oF$ | 7.65 | 7.33 | 6.16 | 7.81 |
| | 8.35 | 7.76 | 6.70 | 7.60 |
| | 3.61 | 2.29 | 2.62 | 2.23 |
| $104^o$ | 3.31 | 2.57 | 2.21 | 3.31 |
| | 3.46 | 2.43 | 2.20 | 2.77 |

Note:

*Asphalt Content is 5.5% by total weight of mix.

Table 7.3: Tensile Modulus of Deformation Values in $10^3$ psi for Compacted Specimens at Various Testing Temperatures

| Testing Temperature | Mix Type $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| | 137.13 | 120.98 | 100.00 | 108.48 |
| 32°F | 128.77 | 109.75 | 98.78 | 112.18 |
| | 114.85 | 106.85 | 99.37 | 115.21 |
| | 20.50 | 22.10 | 19.80 | 25.10 |
| 72°F | 24.60 | 20.50 | 19.30 | 24.00 |
| | 25.20 | 23.70 | 19.00 | 26.70 |
| | 10.32 | 8.15 | 8.30 | 8.12 |
| 104°F | 9.76 | 8.39 | 7.97 | 9.48 |
| | 10.03 | 8.52 | 8.06 | 8.95 |

Note:

*Asphalt Content is 5.5% by total weight of mix.

Table 7.4: Failure Tensile Strain Values in 1/1000 for Compacted Specimens at Various Testing Temperatures

| Testing Temperature | Mix Type $(AC\text{-}20)_0$ | $(AC\text{-}20)_1$ | $(AC\text{-}20)_2$ | $(AC\text{-}20)_3$ |
|---|---|---|---|---|
| | 4.04 | 4.48 | 4.64 | 4.60 |
| $32^oF$ | 4.24 | 4.72 | 4.92 | 4.76 |
| | 5.05 | 4.96 | 4.78 | 4.93 |
| | 9.04 | 7.14 | 7.68 | 6.33 |
| $72^oF$ | 7.86 | 7.50 | 7.68 | 6.33 |
| | 7.23 | 6.78 | 8.14 | 6.78 |
| | 6.30 | 6.75 | 6.75 | 6.65 |
| $104^oF$ | 6.25 | 6.79 | 6.65 | 6.75 |
| | 6.28 | 6.81 | 6.70 | 6.59 |

Note: Asphalt Content is 5.5% by total weight of mix.

addition, the graphical representation of the relationship between test temperature and these parameters are illustrated in Figures 7.2 through 7.5. At every specific temperature level, $(AC-20)_0$ mixtures indicated higher tensile strength, stiffness and modulus of deformation values followed by $(AC-20)_3$, $(AC-20)_1$ and $(AC-20)_2$ recycled mixtures respectively. However, the reduction in strength and stiffness values for all mixtures due to the increase in testing temperature were almost identical as can be observed from Figures 7.2 through 7.5. The slopes representing these reduction rates were almost parallel.

Failure tensile strain (Figure 7.5) for all mixtures increased with the increase in testing temperature from 32°F to 72°F as expected, but decreased with the increase in testing temperature from 72°F to 104°F. This could be attributed to the fact that at a low temperature level (32°F), the mixtures were more brittle and failure was controlled by the limited strain. On the other hand at high temperature (104°F) the strength or stiffness was low enough to allow the specimens to fail at a high deformation level and hence, failure was controlled by the limited strength.

Higher changes in failure strain were observed for $(AC-20)_0$ mixtures followed by $(AC-20)_2$, $(AC-20)_1$ and $(AC-20)_3$ mixtures respectively, with the changes in testing temperature as can be noted by comparing slopes (Figure 7.5).

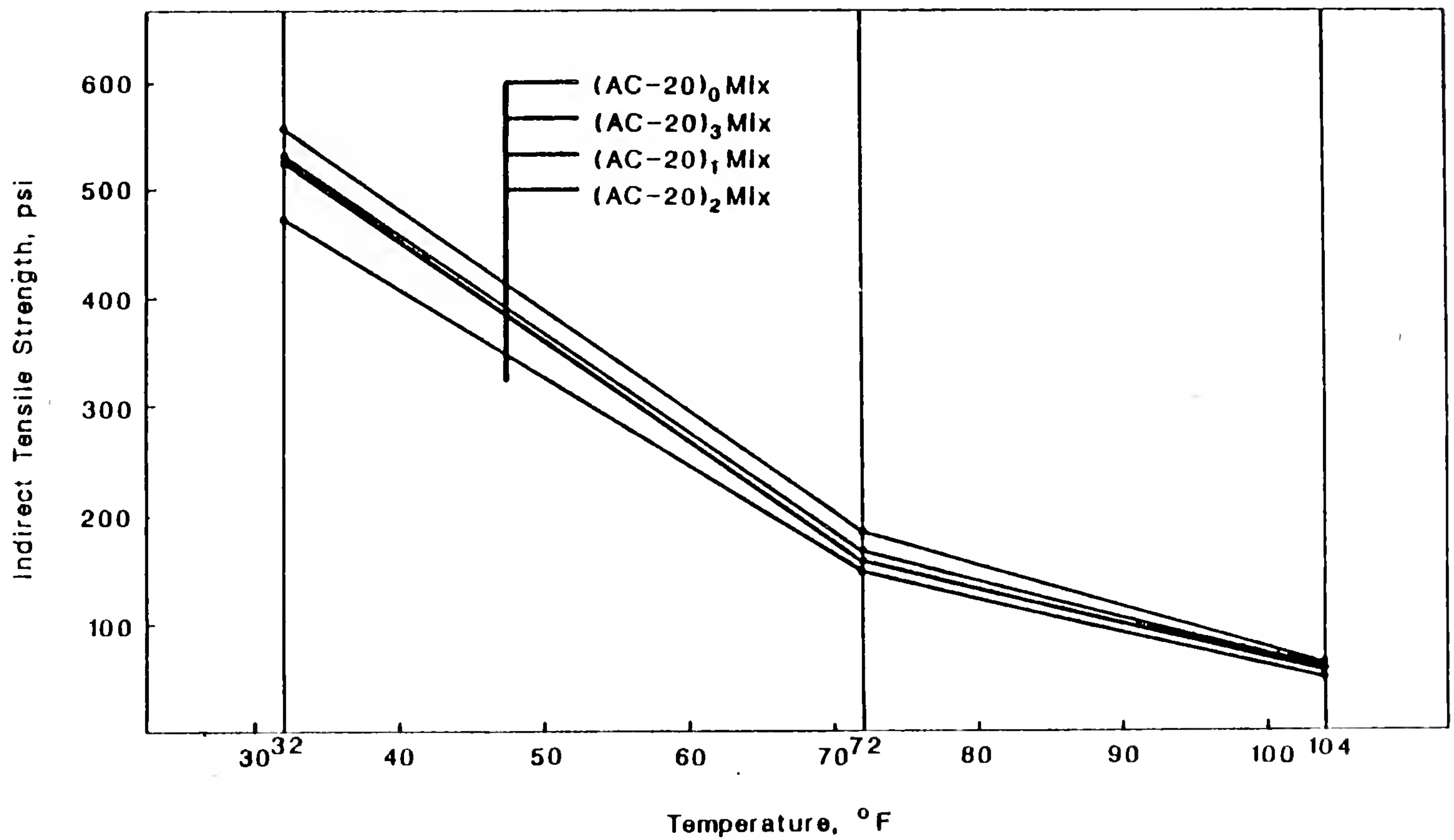



Figure 7.2 Effect of Testing Temperature on The Indirect Tensile Strength

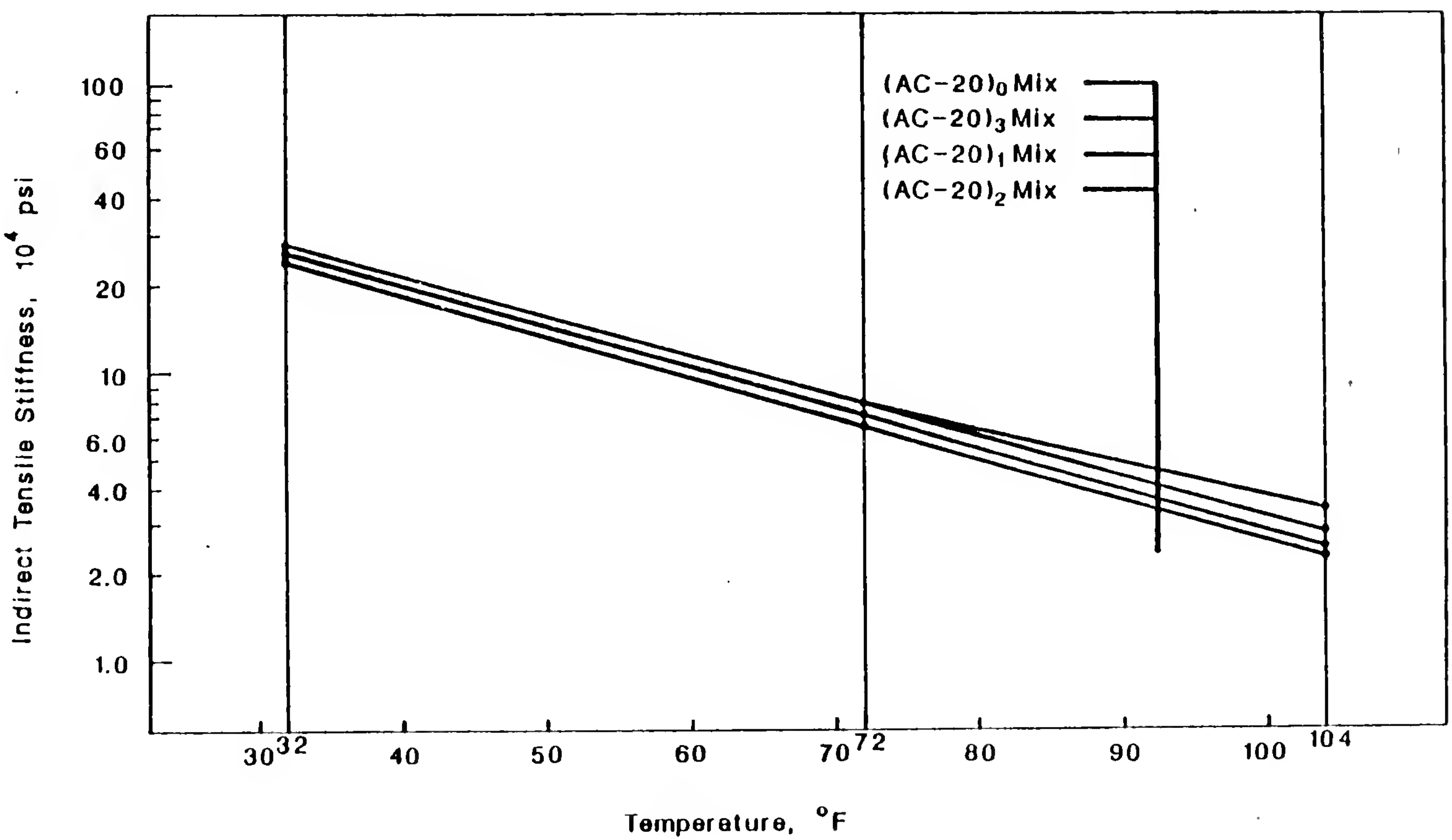



Figure 7.1 Effect of Testing Temperature on The Indirect Tensile Stiffness

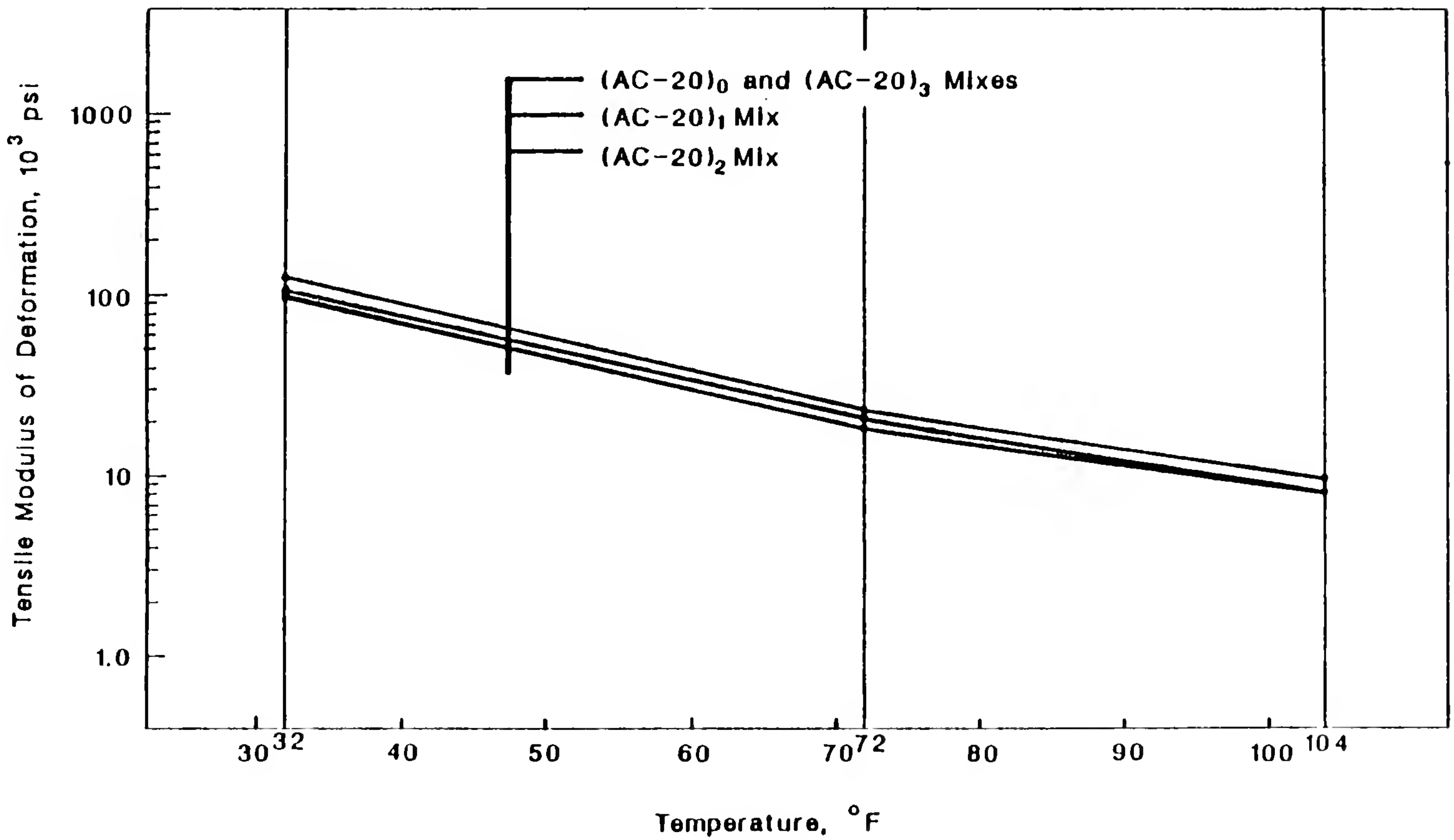



Figure 7.4 Effect of Testing Temperature on The Tensile Modulus of Deformation

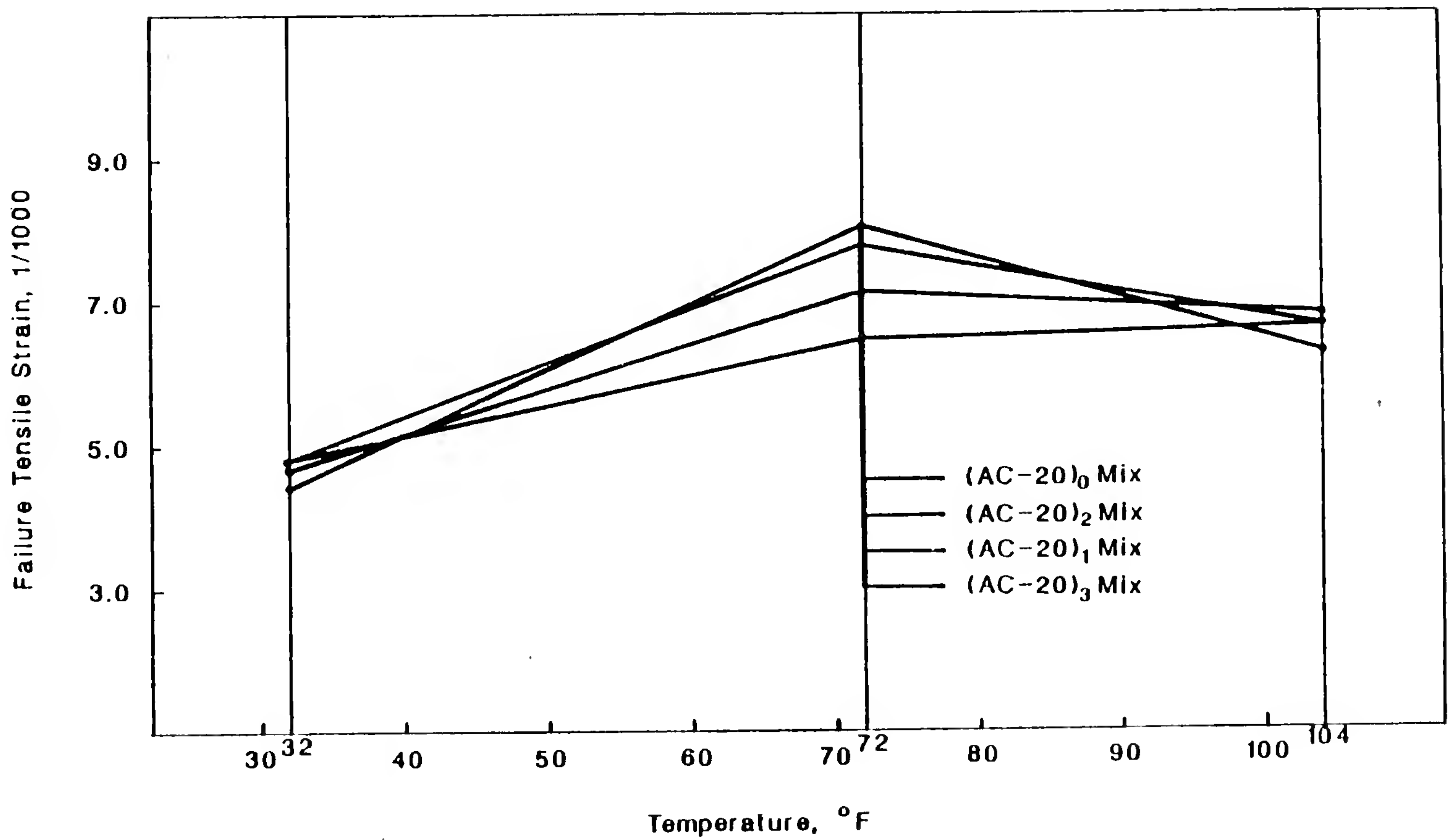



Figure 7.5 Effect of Testing Temperature on The Failure Tensile Strain

## 7.3. Age Hardening Behavior

Compacted specimens representing $(AC-20)_0$, $(AC-20)_1$, $(AC-20)_2$ and $(AC-20)_3$ mixtures were artificially aged by storage in an oven at 140°F for 2 weeks. Asphalt content in all specimens was 5.5%. The aged specimens were then characterized by the following parameters:

1. Pulse velocity (Tables 7.5 and 7.6 and Figures 7.6 and 7.7).

2. Resilient Modulus (Table 7.7 and Figure 7.8).

3. Indirect Tensile Strength (Table 7.8 and Figure 7.9).

4. Indirect Tensile Stiffness (Table 7.9 and Figure 7.10).

5. Failure Tensile Strain (Table 7.10 and Figure 7.11).

6. Tensile Modulus of Deformation (Table 7.11 and Figure 7.12).

The above parameters were obtained at a testing temperature of 72°F and compared with the same parameters obtained for non aged specimens.

Tables 7.5 through 7.11 represent the above six response variables values for the compacted specimens before and

Table 7.5: Effect of Artificial Aging on Pulse Velocity Values, in 1000 ft/sec, of the Compacted Mixtures

| Mix Type | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| After | 11.36 | 11.40 | 11.20 | 11.16 |
| Aging | 11.38 | 11.57 | 11.86 | 11.24 |
| | 11.40 | 11.49 | 11.53 | 11.20 |
| Before | 11.14 | 10.66 | 11.25 | 10.69 |
| Aging | 11.55 | 11.24 | 10.49 | 10.65 |
| | 11.16 | 10.99 | 11.10 | 11.00 |

Table 7.6: Effect of Artificial Aging on Modulus of Elasticity Values, in $10^6$ psi, of the Compacted Mixtures.

| Mix Type | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| After | 2.574 | 2.600 | 2.495 | 2.485 |
| Aging | 2.569 | 2.666 | 2.799 | 2.546 |
| | 2.572 | 2.633 | 2.647 | 2.516 |
| Before | 2.421 | 2.234 | 2.531 | 2.302 |
| Aging | 2.672 | 2.505 | 2.205 | 2.290 |
| | 2.452 | 2.375 | 2.469 | 2.439 |

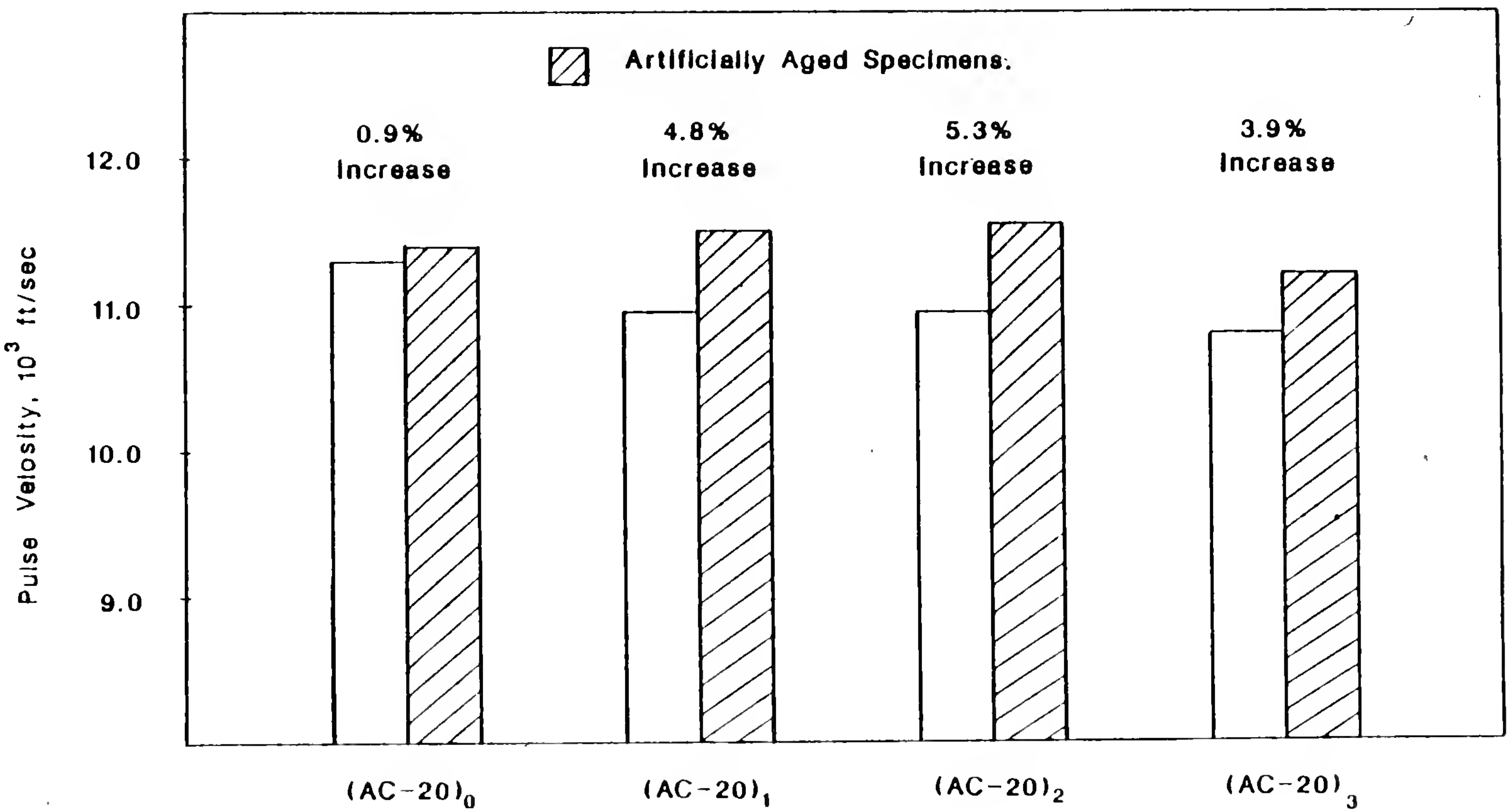



Figure 7.6 Effect of Artificial Age Hardening on Pulse Velocity Through Compacted Mixtures

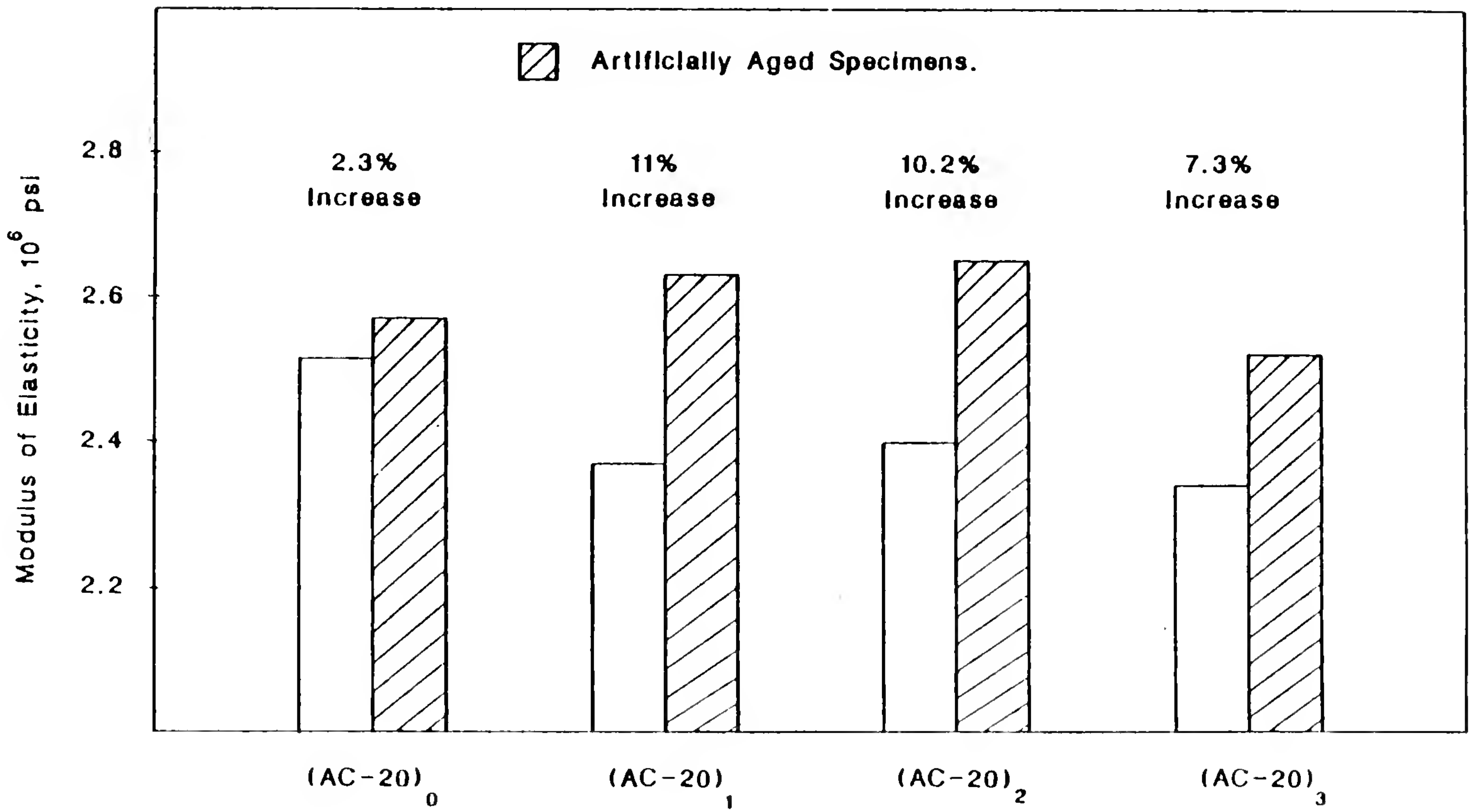



Figure 7.7 Effect of Artificial Age Hardening on Modulus of Elasticity of Compacted Mixtures

Table 7.7: Effect of Artificial Aging on Resilient Modulus Values, in $10^6$ psi, of the Compacted Mixtures

| Mix Type | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| After | 1.379 | 1.245 | 0.961 | 0.788 |
| Aging | 1.700 | 1.707 | 1.394 | 0.822 |
| | 1.540 | 1.476 | 1.178 | 0.805 |
| Before | 0.755 | 0.653 | 0.675 | 0.671 |
| Aging | 0.936 | 0.648 | 0.706 | 0.697 |
| | 0.717 | 0.659 | 0.736 | 0.752 |

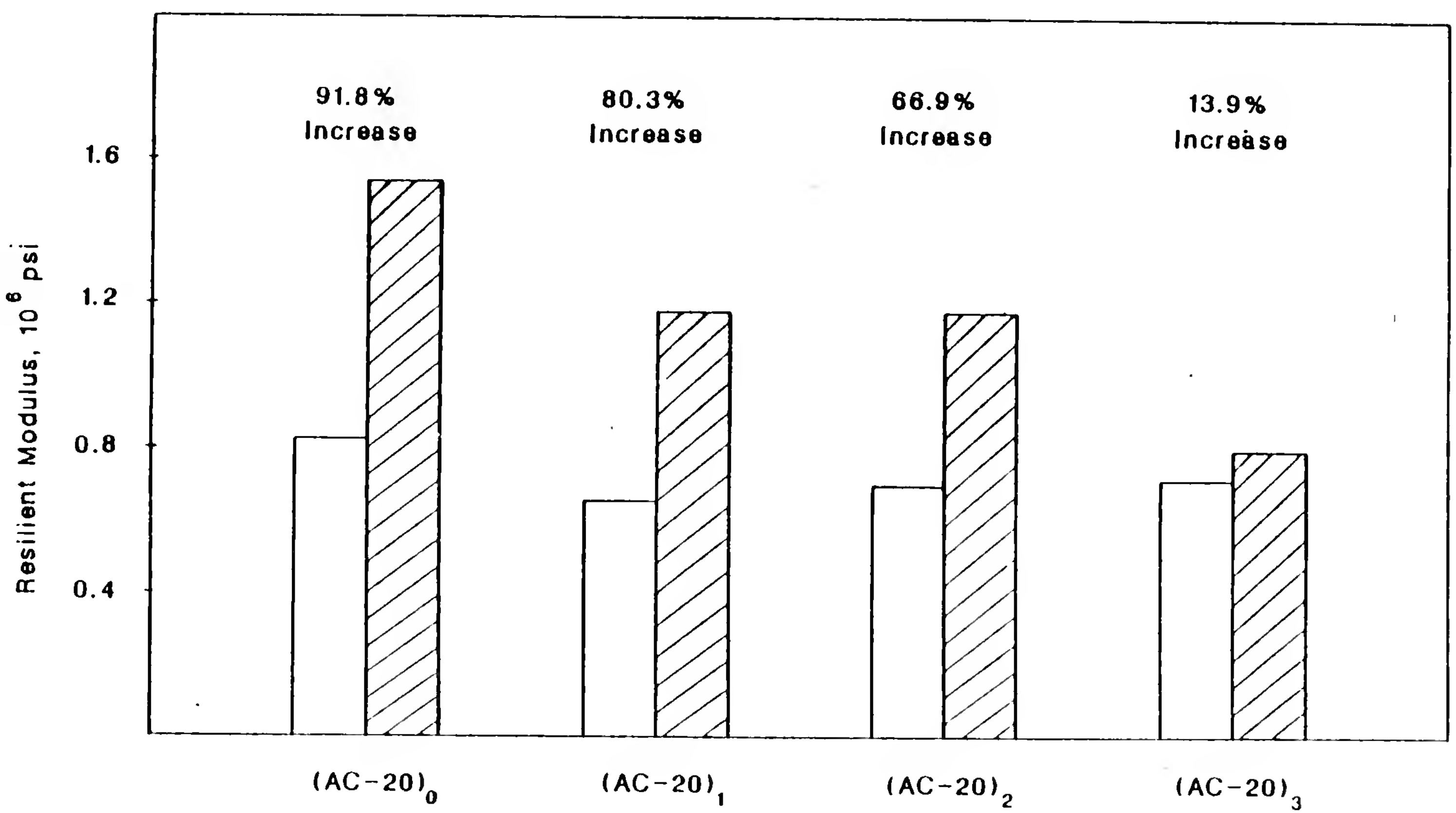



Figure 7.8 Effect of Artificial Age Hardening on Resilient Modulus of Compacted Mixtures

Table 7.8: Effect of Artificial Aging on Indirect Tensile Strength Values, in psi, of the Compacted Mixtures.

| Mix Type | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| After | 257 | 211 | 197 | 156 |
| Aging | 273 | 217 | 220 | 159 |
| | 265 | 214 | 209 | 179 |
| Before | 185 | 158 | 152 | 159 |
| Aging | 193 | 154 | 148 | 152 |
| | 182 | 161 | 155 | 181 |

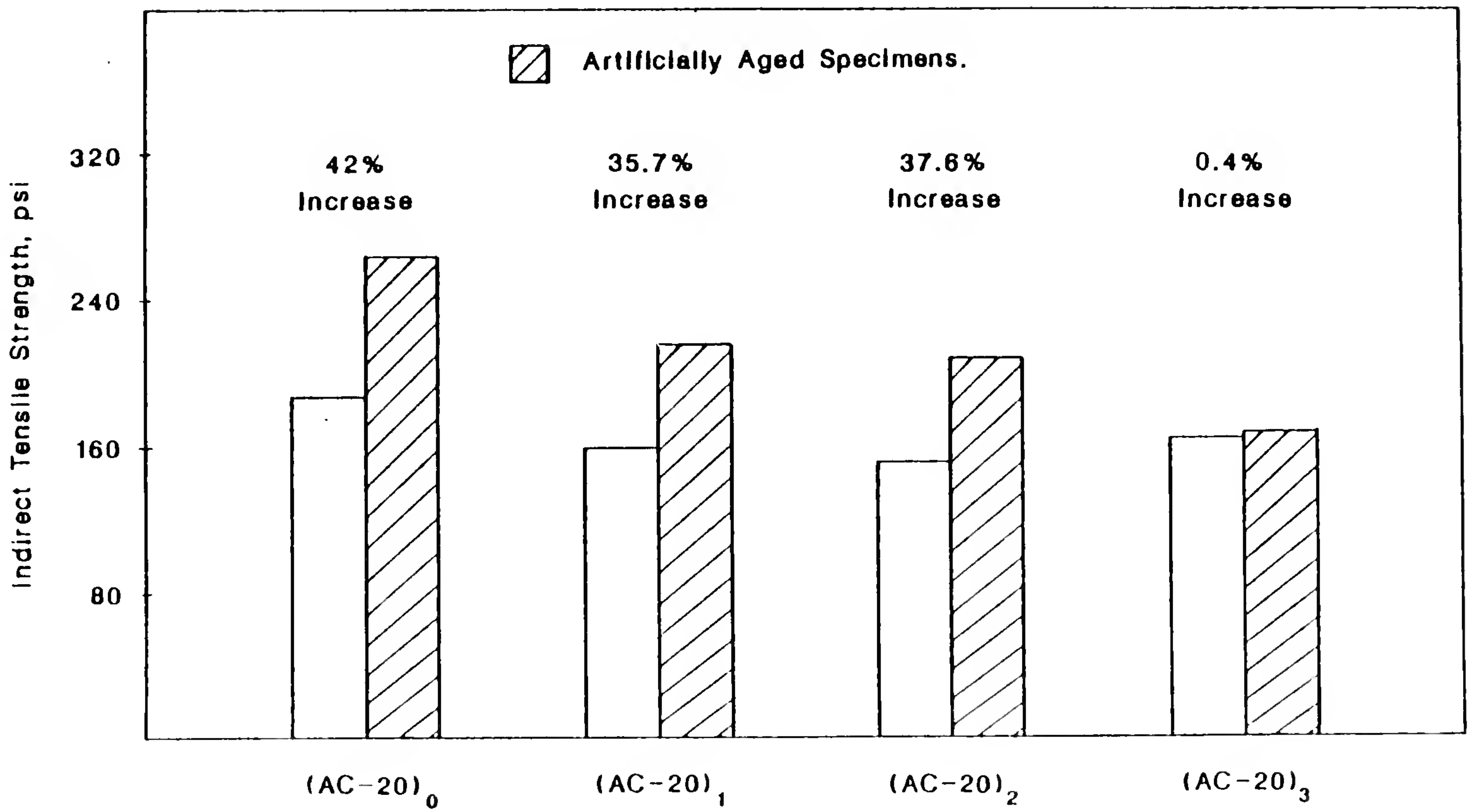



Figure 7.9 Effect of Artificial Age Hardening on Indirect Tensile Strength of Compacted Mixtures

Table 7.9: Effect of Artificial Aging on Indirect Tensile Stiffness Values, in $10^4$ psi, of the Compacted Mixtures

| Mix Type | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| After | 12.78 | 10.99 | 10.35 | 9.56 |
| Aging | 13.33 | 11.05 | 12.11 | 9.28 |
| | 13.06 | 11.02 | 11.23 | 9.42 |
| Before | 8.00 | 6.91 | 7.01 | 8.02 |
| Aging | 7.65 | 7.33 | 6.16 | 7.81 |
| | 8.35 | 7.76 | 6.70 | 7.60 |

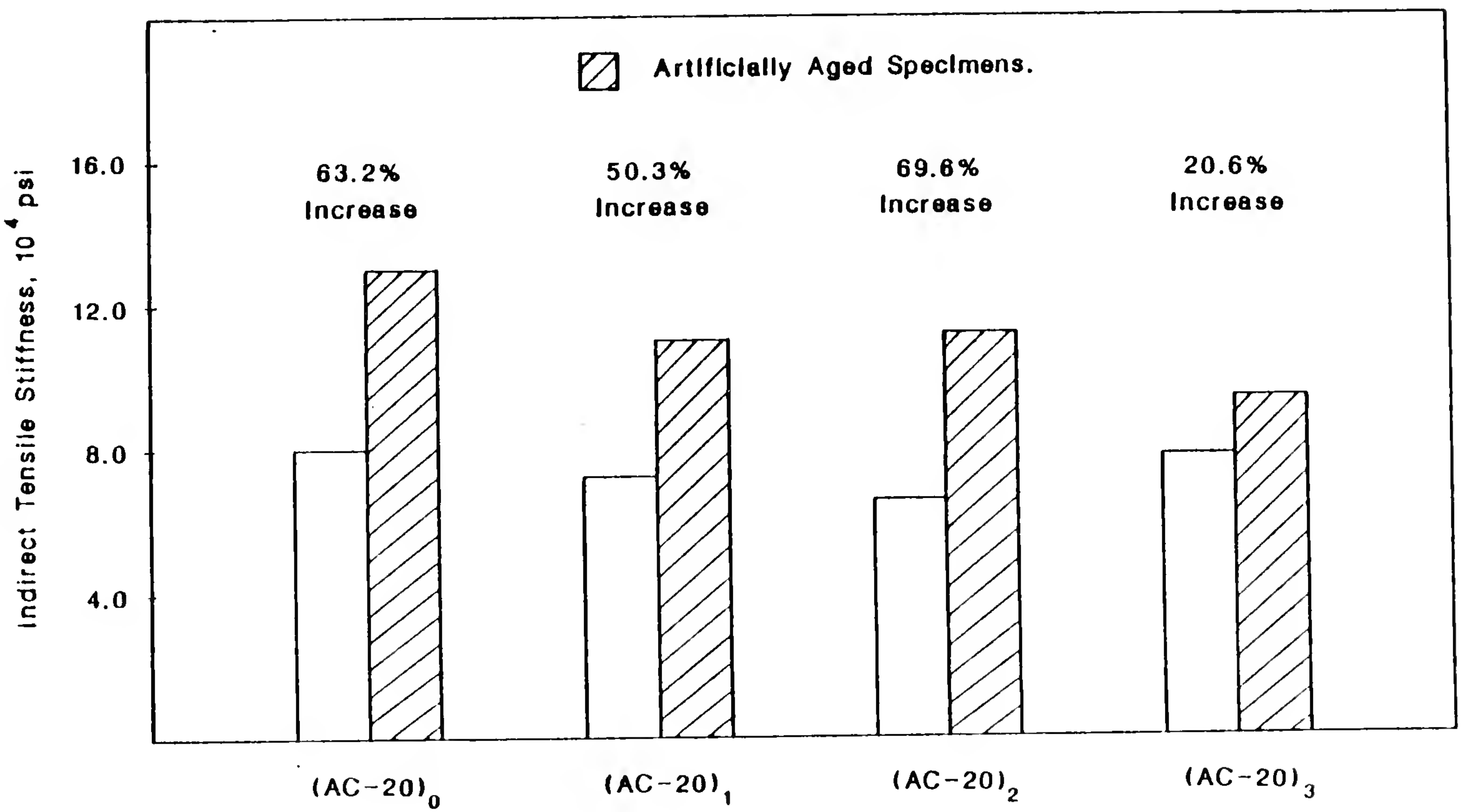



Figure 7.10 Effect of Artificial Age Hardening on Indirect Tensile Stiffness of Compacted Mixtures

Table 7.10: Effect of Artificial Aging on Failure Tensile Strain Values in 1/1000, of the Compacted Mixtures.

| Mix Type | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| After | 5.88 | 5.70 | 5.60 | 6.33 |
| Aging | 5.97 | 6.33 | 5.88 | 6.06 |
| | 5.93 | 6.02 | 5.74 | 6.96 |
| Before | 9.04 | 7.14 | 7.68 | 6.33 |
| Aging | 7.86 | 7.50 | 7.68 | 6.33 |
| | 7.23 | 6.78 | 8.14 | 6.78 |

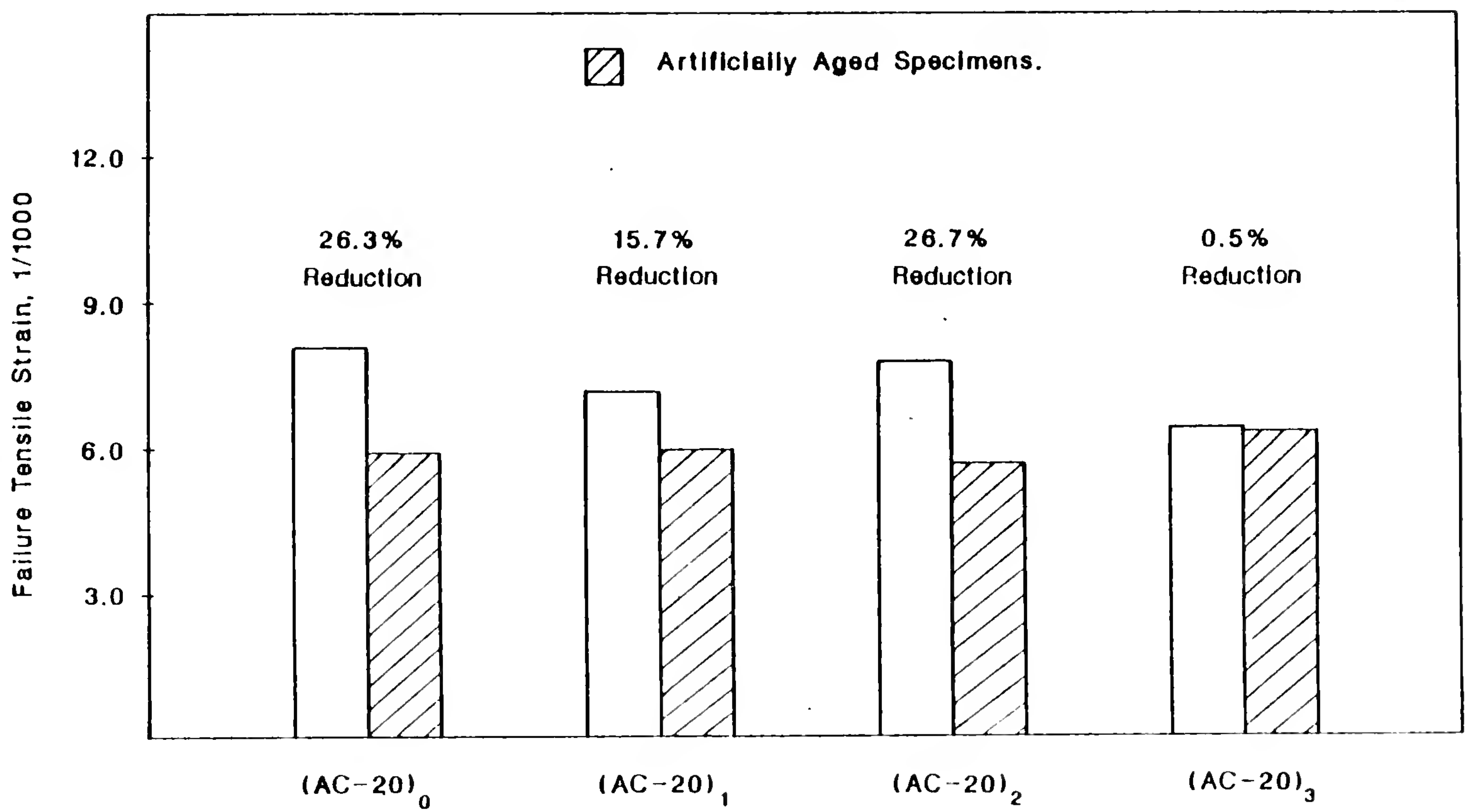



Figure 7.11 Effect of Artificial Age Hardening on Failure Tensile Strain of Compacted Mixtures

Table 7.11: Effect of Artificial Aging on Tensile Modulus of Deformation Values, in $10^3$ psi, of the Compacted Mixtures

| Mix Type | $(AC-20)_0$ | $(AC-20)_1$ | $(AC-20)_2$ | $(AC-20)_3$ |
|---|---|---|---|---|
| After | 43.71 | 37.02 | 35.18 | 24.65 |
| Aging | 45.73 | 34.28 | 37.42 | 26.24 |
| | 44.69 | 35.55 | 36.41 | 25.72 |
| Before | 20.5 | 22.1 | 19.8 | 25.1 |
| Aging | 24.6 | 20.5 | 19.3 | 24.0 |
| | 25.2 | 23.7 | 19.0 | 26.7 |

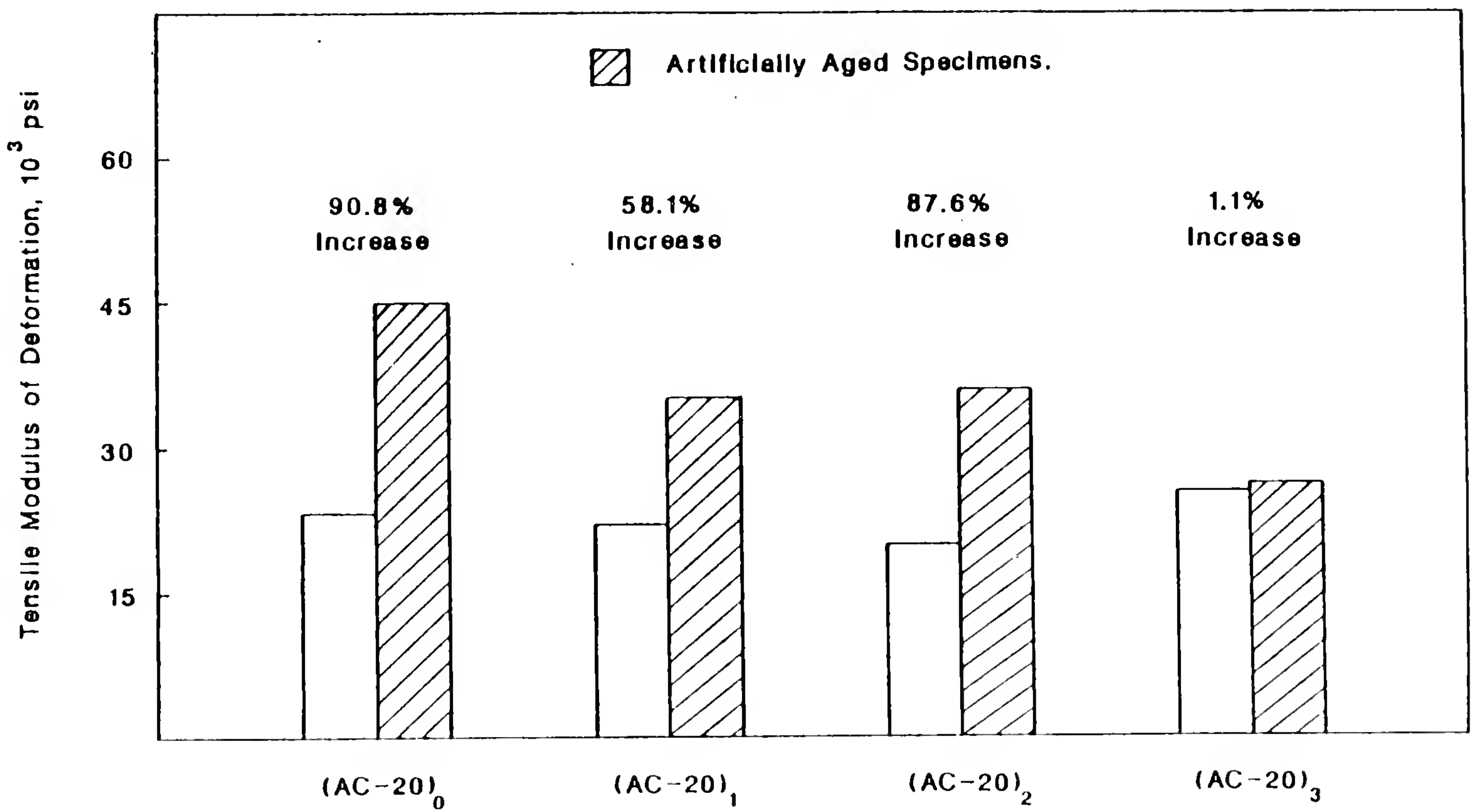



Figure 7.12 Effect of Artificial Age Hardening on Tensile Modulus of Deformation of Compacted Mixtures

after the artificial aging process. The changes in these response variables due to artificial aging is also graphically illustrated in Figures 7.6 through 7.12.

## Pulse Velocity Test

The results for the pulse velocity test did not detect significant differences between the virgin mixture and the three recycled mixtures before and after aging, i.e., mixture type factor was not significant. On the other hand, the artificial aging factor was significant at = 0.05. The aging process caused an increase in pulse velocity values by 1 to 5% (Figure 7.7). A similar trend was obtained for the modulus of elasticity estimated from pulse velocity values and age hardening resulted in an increase in modulus of elasticity values by 2 to 11%.

## Resilient Modulus Test

Drastic increases in the resilient modulus values were caused by the artificial aging process. For virgin mixtures the modulus values increased by 92%. Recycled mixtures modulus values increased by 80%, 67% and 14% (Figure 7.8) due to artificial aging for mixtures modified by AC-2.5, AE-150 and Mobilsol-30 respectively. This could imply that the aging process may be more detrimental for virgin mixture than the recycled mixtures.

Indirect Tensile Test

The tensile strength for a virgin mixture increased by 42% due to aging while for recycled mixtures it increased by 36%, 38% and 0.4% for mixtures modified by AC-2.5, AE-150 and Mobilsol-30 respectively. For the tensile stiffness values these percent increases were 63%, 50%, 70% and 20% respectively.

Failure tensile strain decreased for all mixtures due to aging. Artificial aging caused the failure tensile strain to be 26% lower than original for virgin mixture. For recycled mixtures the percent decrease was 27%, 16% and 0.5% for mixtures modified by AE-150, AC-2.5 and Mobilsol-30 respectively. Mixtures modified by Mobilsol-30 as a rejuvenator was the least affected by the aging process (Figure 7.11).

The modulus of deformation increased by 91% for virgin mixture due to aging while for recycled mixtures modified by AC-2.5, AE-150 and Mobilsol-30 it increased by 38%, 88% and only 1% respectively.

## 7.4. Summary of Results

Long term behavior of recycled mixtures was investigated and compared with a virgin mixture. The time dependent viscoelastic behavior was simulated by loading rate and

temperature dependent behaviors, while the age hardening behavior was simulated by storage of specimens for two weeks at 140$^{o}$F. The main findings can be summarized as follows:

1. Virgin and recycled mixtures undergo reduction in stiffness and strength properties with the increase in loading rate. This reduction was slightly lower for virgin mixture. Permanent deformation potential was almost identical for all mixtures.

2. Virgin mixture stiffness and strength properties were better than recycled mixtures at each specific testing temperature. However, the reduction in strength and stiffness values for all mixtures (virgin or recycled) due to the increase in testing temperature were almost identical.

3. Artificial aging process caused an increase in the strength and stiffness values as well as a reduction in the failure tensile strain values for all virgin and recycled mixtures. Virgin mixture and recycled mixture with AE-150 as a rejuvenator tend to age more rapidly than other recycled mixtures.

4. Resilient modulus and indirect tensile test parameters were more sensitive to long term properties of the virgin and recycled mixtures than the pulse velocity test parameters. Both tests are potential candidates

for the study of long term behavior of recycled mixtures.

# CHAPTER 8

# SUMMARY AND CONCLUSIONS

The main goal of this extensive laboratory study was the characterization of hot mix recycled bituminous material. Three rejuvenating agents; AC-2.5, AE-150 and Mobilsol-30, have been used to produce recycled mixtures. In addition, AC-20 was employed to produce a virgin mixture which was used for comparison purposes. It should be important to indicate that the results obtained herein may be limited to the materials used and test conditions applied. The main conclusions can be summarized as follows:

1. Stage extraction of hard asphalt film present in the recycled asphalt pavement (RAP) indicated a non uniform consistency distribution. Outer components were severely hardened while the inner components (at asphalt-aggregate interface) retained its initial consistency at the time of construction.

2. Recycling agents are most effective on the outer components of the old asphalt material.

3. Rejuvenated binders having the same consistency as a virgin binder may have hardening rates and temperature susceptibility different from the virgin binder.

4. The thin film oven test was identified as a potential added procedure in identifying recycling agents having a tendency to cause compatibility problems for the recycled pavement.

5. AE-150 caused the recycled binder to be more temperature susceptible and have higher hardening rate. In addition, a brittle skin tended to form on all thin film oven test residues and was easily separated from the rest of the sample when AE-150 was used as a rejuvenator.

6. AC-2.5 and Mobilsol-30 usages as rejuvenators resulted in binders with slower hardening rate than AC-20.

7. Virgin mixture stiffness, resilient modulus and strength properties were in general better than those of recycled mixtures. However, this outcome may be limited to the material used in this study.

8. Recycled mixtures, with AE-150 as a rejuvenator, stiffness and strength values were remarkably lower than virgin and other recycled mixtures.

9. Hveem stability values for both virgin and recycled mixtures were above the Asphalt Institute minimum specified limit for mixtures used under heavy traffic category by about 20%. However, the test failed in

discriminating between the mixtures (virgin or recycled).

10. Pulse velocity test parameters were neither sensitive to binder content nor to binder type present in the mixtures.

11. Resilient modulus test results were very sensitive to both binder content and type. The test can be used for the design of asphalt mixture (virgin or recycled) and the evaluation of recycling agent used.

12. The indirect tensile test appears to be the best for characterization of hot mix recycled asphalt pavements. It was sensitive to binder content and type. In addition, it gives four response variables, each of which can be used for evaluation of recycled mixtures. The test parameters are strongly correlated with the resilient modulus and can be used to predict its value with minimum error. The test is very simple and inexpensive and can be used in addition to conventional tests (Hveem or Marshall) for quality assurance of recycled mixes.

13. Marshall stability and flow values for all mixtures (virgin and recycled) were within Asphalt Institute specification limits for heavy traffic category bituminous mixes.

14. Differences in the long term time dependent viscoelastic behavior of virgin and recycled mixtures were not proven with certainty. The virgin mixture was superior to recycled mixtures when the time dependent behavior was simulated by changes in loading rates. However, the virgin and recycled mixtures gave almost identical behavior when the time dependent behavior was simulated by changing testing temperature.

15. Long term aging characteristics of recycled mixtures were superior to virgin mixture except for those recycled mixtures with AE-150 as a rejuvenator. The virgin mixture appeared to age more rapidly than the other two recycled mixtures.

# CHAPTER 9

# RECOMMENDATIONS FOR FURTHER RESEARCH

The author would like to make the following recommendations for further research.

1. The use of the indirect tensile test as an additional specified criterion for evaluation of hot mix recycled asphalt pavement should be further studied. The test sensitivity to binder content and binder characteristics would help to control both amount and type of recycling agent to be used. In addition, the strong correlation between the test parameters and the resilient modulus may be used to predict the modulus values required for theoretical method of pavement thickness design.

2. The use of HP-GPC analysis for the determination of the amount and the appropriate type of recycling agents required for rejuvenating the salvaged binder present in the old pavement should be developed. Studies should be conducted to determine possible relationship between HP-GPC data and pavement long term aging performance.

3. Fatigue properties of hot recycled asphalt mixes which govern the service life of pavement material should be

studied. The relationship between fatigue properties of various recycled mixtures and parameters such as viscosity, type of recycling agent and the resulting binder characteristics should be established.

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